METHODS TO REDUCE RECTAL TEMPERATURE DECLINE OF NEWBORN PIGLETS AND THE EFFECT OF CROSS-FOSTERING STRATEGIES ON PIGLET PRE-WEANING GROWTH AND MORTALITY

BY

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DISSERTATION

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ABSTRACT

There have been significant increases in the average litter sizes of commercial sows over recent decades. As a result, average piglet birth weight has decreased, and the number of low birth weight piglets (i.e., < 1 kg) has increased. Lower birth weight piglets have higher levels of mortality, particularly associated with hypothermia and starvation. Larger litters often exceed the number of functional teats, increasing competition for teat access, and low birth weight piglets have a reduced ability to compete compared to heavier littermates. The research conducted for this thesis focused on reducing pre-weaning mortality through limiting piglet temperature decline in the early postnatal period and by providing an understanding of the fundamental components of cross-fostering.

Five studies were conducted to determine the typical piglet temperature decline in the early postnatal period and evaluate the effect of practical interventions (drying using various methods, warming, drying and warming, or providing supplemental oxygen) on this temperature decline. In addition, the impact of the most effective method at reducing the extent and duration of temperature decline (the combination of drying and warming) was evaluated for piglet pre-weaning mortality. Drying piglets at birth reduced ($P \leq 0.05$) piglet temperature decline within the first 2 h after birth, with no differences between drying methods (with a desiccant or paper towels). Warming piglets was as effective ($P > 0.05$) as drying at minimizing postnatal temperature decline, with the combination of these two approaches being the most effective ($P \leq 0.05$) method. Treatment effects were greater ($P \leq 0.05$) under cooler than warmer farrowing room temperatures. Drying and warming reduced ($P \leq 0.05$) pre-weaning mortality compared to undried Control piglets under cooler (< 25°C), but not warmer (≥ 25°C), farrowing room temperatures. These results suggest that drying and warming of piglets at birth is an effective

approach to reducing early postnatal rectal temperature decline, and may reduce pre-weaning mortality except under farrowing room temperatures typically experienced in the summer months.

Four studies were carried out to develop an understanding of fundamental components of cross-fostering for effects on piglet pre-weaning mortality (PWM, morbidity and mortality) and growth. In general, rearing piglets with lower birth weight littermates reduced ($P \leq 0.05$) PWM and increased ($P \leq 0.05$) weaning weights. Reducing within-litter birth weight variation improved performance for low birth weight piglets (i.e. < 1.0 kg), but reduced performance of heavier piglets. Reducing litter size from two above to two piglets below the number of functional teats of the sow reduced ($P \leq 0.05$) PWM and tended ($P = 0.06$) to increase weaning weight. Using piglets from multiple compared to a single litter to form cross-fostered litters reduced ($P \leq 0.05$) PWM, with no effects on weaning weights. The results of these studies suggest that increasing the piglet competition within the litter (by increasing litter size or the weight of littermates) results in increased PWM and decreased weaning weights. In addition, PWM was lower when piglets were mixed with those from other litters, however, the biological or behavioral reasons for this effect require further research. The optimum cross-fostering strategy to maximize pre-weaning piglet performance is likely to be dictated by the birth weight distribution of the population in question, and the cost of reducing litter size (which, for example, would require the use of more nurse sows) compared to the benefit of increased piglet performance.

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CHAPTER 1: Piglet temperature literature review

Introduction

Pre-weaning mortality is a source of significant economic loss for the U.S. swine industry, a major welfare concern, and presents a negative public image of the industry. According to PigChamp (2018) data, pre-weaning mortality levels have increased on U.S. units over recent years and currently average around 15% of piglets born alive. A major factor associated with increasing pre-weaning mortality is the decrease in average piglet birth weight associated with the increases in litter sizes that have occurred in commercial dam lines. Estimates suggest that approximately 15% of piglets born are of low birth weight (i.e., weighing < 1 kg) and that mortality in these piglets is extremely high, often exceeding 50% (Feldpausch et al., 2016).

A major pre-disposing factor for pre-weaning mortality associated with low birth weights is low body temperature in the early postnatal period. All piglets experience a decline in body temperature immediately after birth and this "chilling" can be a cause of early mortality, pre-disposing piglets to other causes of mortality such as crushing or infection (Shankar et al., 2009). Low birth weight piglets experience the largest postnatal body temperature decline and have the highest levels of pre-weaning mortality (Tuchscherer et al., 2000). However, our understanding of body temperature changes in the postnatal period, other than in a general sense, is extremely limited, especially under typical commercial conditions. Understanding these changes in body temperature and the effectiveness of potential intervention strategies are critical first steps in developing practically applicable approaches to minimizing temperature decline and to reducing associated mortality.

Early Postnatal Temperature Changes of Undried Piglets

Piglets are highly susceptible to chilling immediately after birth, which is a major predisposing factor for pre-weaning mortality (Curtis, 1974). They are born wet and evaporation of this moisture removes heat from the body. They are also born into an environment that is much cooler than they experience *in utero* (around 39°C), with farrowing room temperatures normally being at 22 to 24°C. This negative temperature gradient results in significant heat loss from the piglet to the environment. In addition, piglets are born with limited body surface insulation (thin hair coat and low subcutaneous fat reserves). Because of these factors, all piglets experience a decrease in body temperature until they dry and produce sufficient body heat to increase body temperature and maintain homeothermy. The extent and duration of this temperature decline varies between piglets, depending on factors such as birth weight, the environment into which they are born, and management protocols utilized.

A number of studies have investigated body temperature changes in piglets during the early postnatal period, however, the methodology used and conditions experienced varied markedly between studies. Some of the major differences between studies included the method and timing of temperature measurement, the study environmental conditions, and piglet characteristics, particularly birth weight. Consequently, it is difficult to compare the results of these studies or to determine the normal temperature decline expected under typical conditions. The studies discussed below used management protocols with minimal piglet interventions and no drying to determine typical postnatal temperature decline under standard conditions.

The key results from the studies that have measured piglet birth temperatures are summarized in Table 1.1. Most studies used rectal temperature as the method of measuring piglet body temperature. There was considerable variation in piglet rectal temperatures at birth across the studies with mean temperatures ranging from 37.8°C (Vasdal et al., 2011) to 40.5°C (Pomeroy et al., 1953). There was also considerable variation in individual piglet temperatures within studies; for example, Kammersgaard et al. (2011) reported piglet birth temperatures between 37.0 and 41.5°C. Two studies (Caldara et al., 2014; Santiago et al., 2019) used thermal imaging to measure piglet body surface temperature, which produced lower values for temperatures than studies reporting rectal temperatures. It is not clear why there was such high variation between or within studies for rectal temperatures at birth. However, these results suggest that the timing of piglet "birth" temperature may have varied between studies, as piglet temperature declines quickly within the first few minutes after birth (Pattison et al., 1990).

The time after birth of minimum piglet temperature varied across studies, largely due to differences in times of measurements. Caldara et al. (2014) reported the lowest body surface temperature at 15 min after birth. Xiong et al. (2018), Pattison et al. (1990), Andersen and Pedersen (2015), Le Dividich and Noblet (1981), and Cooper et al. (2019) reported the lowest rectal temperatures at 30 min after birth. McGinnis et al. (1981), Vila (2013), and Tuchscherer et al. (2000) found the lowest rectal temperatures at 1 h after birth. However, none of these three studies measured temperature between birth and 1 h. Pomeroy (1953) found the lowest rectal temperatures occurred between 80 and 90 min after birth, however, this was based on only two piglets. Vasdal et al. (2011) and Kammersgaard et al. (2011) reported a minimum rectal temperature at 2 h after birth, however, these studies also did not measure rectal temperature between birth and that time.

The extent of the temperature decline from birth to the minimum temperature also varied across studies. For example, Xiong et al. (2018) and Pattison et al. (1990; investigation 2) both found that the minimum temperature was reached at 30 min after birth, however, the extent of the decline was substantially different, 5.1 and 2.6°C below the birth temperature, respectively. Much of the variation in the extent of this temperature decline may be explained by differences in factors such as the average piglet birth weight, room temperature, or piglet handling and management.

There was considerable variation between studies in the time after birth of the final temperature measurement (Table 1.1). However, the greatest changes in piglet temperature and most of the recovery to birth temperature occurred within the first 24 h after birth. In some studies, the final temperature was measured relatively early after birth and as a result reported relatively low temperatures. For example, Pederson et al. (2016) measured the final rectal temperature at 2 h after birth and showed temperatures of 36.4 and 35.3°C for piglets on slatted and solid flooring, respectively. The majority of studies that measured final temperature between 10 and 24 h after birth showed values approaching those observed at birth (between 38 and 39°C). The only exception was the study by Vasdal et al. (2011), which found temperatures at 24 h of between 37.7 and 37.9°C for undried piglets. However, the room temperature during this study was considerably lower (16 to 20°C) than that of most other studies (Table 1.1), which could in part explain the lower 24 h temperature in the study of Vasdal et al. (2011). Despite the variation in absolute temperatures and extent of temperature decline between studies, the overall conclusion is that all piglets experience a large temperature decrease in the early postnatal period.

Effect of Piglet Birth Weight on Early Postnatal Temperature Changes

Piglet birth weight has been shown in numerous studies to significantly impact postnatal body temperature changes. In this regard, low birth weight piglets are particularly susceptible to chilling. They have a higher body surface area to body volume ratio, and, therefore, relatively greater heat loss. They also generally have lower body fat for insulation (Curtis, 1974) and lower energy reserves (glycogen and fat) for heat production (Lossec et al., 1998). Consequently, light piglets experience a greater postnatal temperature decline which pre-disposes them to higher rates of mortality in the early postnatal period.

Studies that evaluated the effect of birth weight on postnatal temperature changes in piglets have been summarized in Table 1.2. Most studies showed no effect of birth weight on piglet birth temperature. The exception to this was the study of Santiago et al. (2019) which classified piglets on the basis of a vitality score (low, medium, or high) and showed lower weights and temperatures at birth for piglets with low and medium compared to high vitality scores. However, it is not clear whether this temperature difference was due to piglet birth weight or to other factors that differed between piglets with different vitality scores. Most other studies have shown that piglet temperatures at birth were not generally affected by birth weight, and averaged between 37 and 40.5°C.

Studies varied in the approach used to analyze the effect of piglet birth weight on postnatal temperature changes (Table 1.2). Some studies divided piglets into birth weight categories (e.g., Pattison et al., 1990) or quartiles (e.g., Pedersen et al., 2016; Cooper et al., 2019), whereas others used regression analysis to determine the relationship between piglet birth weight and temperature at various times (e.g., Caldara et al., 2014; Andersen and Pedersen, 2015). Studies that compared the mean temperatures for the various birth weight categories or quartiles found that for most times of measurement within the first few hours after birth, lighter birth weight piglets generally had lower temperatures than heavier piglets (Table 1.2). For example, Cooper et al. (2019) showed that temperatures at 30 min after birth were between 0.8 and 1.2°C lower for piglets in the lightest birth weight quartile (35.4°C; mean birth weight of

1.13 kg) compared to piglets from the other three weight quartiles (36.2, 36.6, and 36.6°C; mean birth weights of 1.43, 1.62, and 1.81 kg, respectively). Similarly, Pedersen et al. (2016) found that for undried piglets on a solid floor without supplemental heating, temperature at two hours after birth increased with increasing birth weight; rectal temperatures for the 25th (mean birth weight of 1.18 kg), 50th (mean birth weight of 1.40 kg), and 75th (mean birth weight 1.65 kg) percentiles were 35.5, 36.0, and 36.2°C. In addition, Pattison et al. (1990) found that piglets with birth weights below 1 kg had significantly lower minimum rectal temperatures (which occurred at 30 min after birth) by between 1.6 and 2.3°C compared to piglets with birth weights of 1.0 to 1.5 kg, or > 1.5 kg, respectively (mean temperatures of 33.9, 35.5, and 36.2°C for each birth weight category, respectively).

A number of studies regressed body temperature against piglet birth weight at various times after birth and all showed positive relationships (Table 1.2). However, the magnitude of the regression coefficient varied depending on the measurement time after birth and were generally greater within the first hour than at subsequent measurement times. For example, Caldara et al. (2014) found that body surface temperature increased by 0.481 and 0.473°C per kg increase in birth weight at 30 and 45 min after birth, respectively. Andersen and Pedersen (2015) found that rectal temperature increased by between 0.31 and 0.39°C per kg increase in birth weight at times between 15 and 60 min after birth; however, the effect of birth weight was substantially lower at 24 h (0.07°C increase in temperature per 1 kg increase in birth weight). Pattison et al. (1990) reported that at 30 min after birth (the time of the minimum piglet rectal temperature), rectal temperature increased by 0.19°C per 100 g increase in piglet birth weight. Dividich and Noblet (1981) reported that birth weight accounted for a significant but decreasing proportion of the variation in piglet rectal temperature with increasing time after birth from 18 min (76%) to 8.2 h (25%).

In conclusion, all studies have shown that lighter piglets have lower temperatures than heavier piglets in the early postnatal period. In support of this, Kammersgaard et al. (2011) concluded that birth weight was the single most important variable determining piglet rectal temperature at 2 h after birth.

As previously discussed, piglet temperatures increased from the minimum observed value and approached birth temperatures by 24 h after birth and these changes were also observed in piglets of all birth weights. Consequently, the effects of birth weight on body temperature decreased as piglets approached 24 h of age, a finding which has also been shown in other studies. For example, Cooper et al. (2019) found differences between birth weight quartiles at 30 min after birth, however these differences disappeared by 24 h after birth, when there was no effect of birth weight quartile. In addition, Le Dividich and Noblet (1981) found that birth weight did not explain a significant proportion of the variation in piglet rectal temperature at 15 h after birth. Pattison et al. (1990) showed that the differences in rectal temperatures between light (< 1.0 kg) and medium (1.0 to 1.5 kg) and heavy (> 1.5 kg) birth weight piglets decreased from 30 min (1.6 or 2.3°C difference compared to medium or heavy piglets, respectively) to 24 h after birth (0.6°C difference compared to both medium and heavy piglets). However, these authors did not report the statistical significance of the differences between these means. Andersen and Pedersen (2015) showed that the regression of rectal temperature against piglet birth weight was significant at all time points between 15 min and 24 h after birth. However, the magnitude of the regression coefficient decreased over time from 0.31°C per kg birth weight at 15 min to only 0.07°C per kg by 24 h after birth (Table 1.2).

Results of this research clearly show that the effect of birth weight on rectal temperature initially increases over the first hour after birth, with light birth weight piglets experiencing the greatest temperature decline. This leads to greater differences in temperature between light (e.g., < 1.0 kg) and heavy (e.g., > 1.5 kg) birth weight piglets at the time minimum temperatures were observed than at other time points. However, this birth weight effect subsequently decreases to a minimal level by 24 h, with temperatures for piglets of all birth weights approaching the levels observed at birth. This suggests that even the lightest piglets have the potential to recover body temperature and achieve homeothermy.

Effect of Drying Piglets at Birth on Early Postnatal Temperature Changes

Drying of piglets at birth has been widely used commercially, yet there is limited published information in the scientific literature either on its effect on postnatal body temperature changes, or on the relative effectiveness of the various approaches that can be used to dry piglets. The limited number of studies that have investigated the effect of drying of piglets on subsequent body temperature changes are summarized in Table 1.3.

As would be expected, none of these studies found an effect of drying piglets on temperature at birth. As previously discussed, there was substantial variation between studies for birth temperature, which ranged from approximately 37°C to 39°C (Table 1.3). All studies showed that the time of the minimum temperature after birth was similar for both dried and undried piglets. For example, Vasdal et al. (2011) found that the minimum temperature for dried and undried piglets occurred at 2 h after birth. McGinnis et al. (1981) showed minimum temperatures occurred at 1 h after birth for both dried and undried piglet treatments. Similarly, Pasca et al. (2008) found that piglets dried either within 2 min of birth or after 10 to 15 min reached minimum temperatures at 1 h after birth; however, this study did not include an undried control treatment.

While the time of the minimum temperature did not differ, most studies found a significant effect of drying piglets at birth on the extent of piglet temperature decline (Table 1.3). McGinnis et al. (1981), Pasca et al. (2008), Berbigier et al. (1978), and Cooper et al. (2019) evaluated different approaches to drying piglets and all of these studies showed significantly higher minimum temperatures for dried compared to undried piglets. However, Vasdal et al. (2011) found no effect of drying piglets at birth (with both straw and paper towels) on rectal temperature at 2 h after birth (Table 1.3). This may be due to the time of measurement used in this study, as the effects of drying seen in other studies were also not observed by this time after birth (e.g., Cooper et al., 2019).

Few studies have measured body temperatures frequently enough to clearly determine the duration of the temperature difference between dried and undried piglets. McGinnis et al. (1981) showed significantly higher temperatures for dried compared to undried piglets at 1 h after birth; however, subsequent temperatures between 2 and 24 h after birth were similar for the two treatments. Similarly, Cooper et al. (2019) found that dried piglets had significantly higher rectal temperatures between 15 and 90 min after birth, however, there were no temperature differences between treatments from 2 to 24 h after birth.

In conclusion, the literature on the effects of drying piglets at birth is extremely limited, and studies did not measure temperatures frequently enough during the early postnatal period to establish effects on piglet temperature changes. Further research is needed to compare practical drying methods and determine the effect of drying on piglet temperature within the early postnatal period.

Effect of Warming of Piglets at Birth on Early Postnatal Temperature Changes

As previously discussed, piglets are born into an environment that is much cooler than they experience *in utero*, which results in a decline in temperature in the early postnatal period. One method to limit this decline is to reduce the temperature gradient by increasing the environmental temperature that the piglets experience after birth. However, increasing the temperature of the farrowing room, although potentially beneficial for the piglets, would lead to heat stress for the sows, resulting in reduced feed intake and milk production (Farmer and Quesnel, 2009). One practical approach to warming piglets without increasing farrowing room temperature is to confine the piglets in a warming box under a localized heat source for a short period of time after birth before returning to the sow. These warming boxes commonly consist of an infrared heat lamp suspended over a plastic storage box; typically, the temperature within the box is between 30 to 40°C. Although warming boxes are widely used in commercial practice, there has been very little published research on the effects of this approach on piglet temperatures during the early postnatal period.

The studies reviewed varied in the heat source used and timing and duration of piglet warming (Table 1.4). Some studies compared differing room temperatures (Pedersen et al., 2015; Berbigier et al., 1978). In other studies, farrowing pens with and without additional localized heated areas were compared, but piglets were not restricted to a heated area (McGinnis et al., 1981; Andersen and Pedersen, 2015; Le Dividich and Noblet, 1981; Christison et al., 1997; Ogunbameru et al., 1991). In the study of Vasdal et al. (2011), all farrowing pens included a heated creep area and treatments involved placing the piglets in this heated area, at the sow's udder, or to the place where they were originally found. Only two studies restricted the piglets within a heated area for a period of time after birth (Pedersen et al., 2016; Pattison et al., 1990).

Three studies measured piglet temperature at birth (Table 1.4; Vasdal et al., 2011; Pattison et al., 1990; and Le Dividich and Noblet, 1981). Of these three studies, only Vasdal et al. (2011) found a difference in birth temperature between treatments, with piglets that were placed in a heated creep area at birth having significantly higher temperatures than those that were not moved from the farrowing pen after birth. It is not clear why this treatment effect on birth temperature occurred, as it would appear that piglet temperatures were measured before any treatment was applied.

Most studies found no effect of piglet warming on the time that piglets reached a minimum temperature, which was generally between 30 min and 2 h after birth (Table 1.4). However, results for the effect of piglet warming on the absolute minimum rectal temperature after birth were highly variable. Most studies showed significantly higher temperatures for piglets that were warmed at or soon after birth compared to those that were not treated (Vasdal et al., 2011; Pederson et al., 2016; Andersen and Pedersen, 2015; Le Dividich and Noblet, 1981; Berbigier et al., 1978). However, two studies found similar minimum temperatures for warmed and untreated piglets (McGinnis et al., 1981; Pattison et al., 1990).

While warming treatments were generally effective at increasing piglet temperature in the early period after birth (Table 1.4), the magnitude of this effect subsequently decreased and was minimal by 24 h after birth, when temperatures approached those observed at birth. Most studies found no effects of piglet warming at this time, with both warmed and untreated piglets reaching their maximum postnatal temperature (Vasdal et al., 2011; Pattison et al., 1990; Andersen and Pedersen, 2015; Table 1.4). However, two studies showed a positive effect of piglet warming on rectal temperature at 24 h (McGinnis et al., 1981; Le Dividich and Noblet, 1981). McGinnis et al. (1981) evaluated two methods to provide localized warming in the farrowing pen (through either increased floor temperature or via a heat lamp); piglets were allowed free access to these warmed areas. There was no effect of either warming method on piglet rectal temperature at 1 h after birth, however, rectal temperatures at 24 h after birth were significantly higher for both treatments that provided access to either a heated floor or a heat lamp compared to the controls.

In conclusion, most published literature has shown that warming piglets in the early postnatal period is effective at reducing piglet rectal temperature decline, particularly when piglets are confined to the heated area. However, most research did not measure temperatures frequently enough after birth to determine the extent and timing of this effect.

Effect of Oxygenation on Piglet Temperature Changes in the Early Postnatal Period and Pre-weaning Mortality

Asphyxiation and associated low blood oxygen levels are commonly observed in piglets at birth, particularly for those born later in the farrowing process (English and Wilkinson, 1982). If piglet birth is delayed after rupture of the umbilical cord, and/or piglets are born encased in placenta, or experience trauma during parturition, they can be asphyxiated and experience elevated levels of mortality (Randall, 1971). In addition, it has been suggested that there is a relationship between piglet blood oxygen levels after birth and rectal temperatures (Herpin et al., 1996), implying that administering oxygen at birth may reduce pre-weaning mortality due to asphyxiation, and/or increase postnatal rectal temperatures.

There has been limited research to determine the effects of administering supplementary oxygen to piglets at birth on piglet temperature in the early postnatal period. Only one study (Herpin et al., 2001) measured the effect of oxygen administration at birth on piglet temperature. This study compared placing piglets in a chamber at 40% oxygen concentration for 20 min after birth to an untreated control (piglets remained with the sow in the farrowing pen without supplemental oxygen administration). There was no effect of oxygen administration on birth temperature (39.4 and 39.3°C for the control and oxygen treatments, respectively), however, piglets given oxygen had higher minimum rectal temperatures (at 30 min after birth; 37.0 vs. 37.5°C for the control and oxygen treatments, respectively). The effects of oxygenation on rectal temperature decreased by 24 h after birth, when piglet temperature recovered to 38.6°C for both treatments. Interestingly, the results of this study suggested that oxygenation modified the relationship between birth weight and rectal temperature at 30 min after birth. For the control treatment, there was a positive relationship between birth weight and rectal temperature, which is consistent with previously discussed studies. However, there was no effect of birth weight on rectal temperature at 30 min after birth for the oxygen treatment. This suggests that oxygenation may be of greatest benefit for reducing the temperature decline of lighter birth weight piglets. Further research is needed to validate these results.

In addition to the study of Herpin et al. (2001) that evaluated the effect of administering oxygen to piglets, Zaleski and Hacker (1993) showed that administering oxygen to sows during farrowing increased sow blood oxygen levels, but had no effect on piglet blood oxygen concentration, piglet vitality, or the rate of stillbirths. In addition, Panzardi et al. (2013) found no relationship between blood oxygen saturation in piglets at birth and piglet mortality in the first 7 d after birth when supplemental oxygen was not provided. In conclusion, there is limited information on the effects of oxygenation on piglet temperature changes in the early postnatal period, and further research is necessary.

Effect of Interventions for Prevention of Hypothermia on Piglet Pre-weaning Mortality

Crushing and starvation are the two most common causes of pre-weaning mortality on commercial swine units (PigChamp, 2018). However, hypothermia is often a major pre-disposing factor for both (Edwards, 2002). As previously discussed, all piglets experience some degree of hypothermia early after birth, with the extent varying due to factors such as birth weight, environmental conditions, or management interventions. Reducing the incidence of hypothermia early after birth should, therefore, decrease piglet pre-weaning mortality. However, there has been limited research on the effects of interventions to reduce early postnatal temperature decline on piglet mortality.

A limited number of studies have reported on the effects of drying or warming of piglets at birth on subsequent performance to weaning (behavior, growth, and mortality); however, most of these studies had insufficient replication to detect practically important differences in mortality levels. Ogunbameru et al. (1991) did not find any significant effects of providing extra heat sources (heat lamp or heater) within the farrowing pen on piglet mortality to weaning. However, Christison et al. (1997) found that piglets that were dried or warmed at birth had lower ($P \leq 0.05$) pre-weaning mortality (6% and 0% for piglets that were dried or warmed, respectively) compared to an untreated Control (21% pre-weaning mortality).

Only one study (Herpin et al., 2001) evaluated the effect of oxygen administration to piglets at birth on pre-weaning mortality, and found no overall effect. However, there was an interaction between birth weight and oxygen treatment for pre-weaning mortality, which was significantly lower for light birth weight piglets (< 1.2 kg) given oxygen compared to untreated control piglets (18.8% vs. 31.6%, respectively). However, medium (1.2 to 1.6 kg) and heavy (> 1.6 kg) that were administered oxygen had similar pre-weaning mortality levels compared to untreated controls (4.6% vs. 2.3% and 7.9% vs. 12.2% for medium and heavy piglets, respectively).

Three studies did not provide supplemental oxygen to piglets, but evaluated the relationship between piglet blood oxygen levels at birth and pre-weaning mortality. Panzardi et al. (2013) found no relationship between blood oxygen levels at birth and piglet mortality to 7 d of age. Herpin et al. (1996) categorized piglets at birth as either highly asphyxiated or normal and found a trend ($P = 0.06$) for the highly asphyxiated piglets to have higher mortality at 10 d of age (42.9% and 19.4%, respectively). Zaleski and Hacker (1993) found no effect of administering oxygen to the sow after the birth of the first piglet for either stillbirths or piglet viability scores at birth. The authors proposed that this lack of an effect may have been due to the longer interval between birth of the second and third piglets in the litter for treated compared to untreated control sows.

Conclusion

In conclusion, all piglets experienced a major decline in temperature in the early postnatal period, and most studies found that the lowest temperatures occurred within the first hour after birth. In addition, of all the factors evaluated, birth weight was the best predictor of rectal temperature variation within the first hour after birth, with lighter birth weight piglets experiencing a greater reduction in temperature than heavier piglets. For most studies reviewed, drying or warming piglets at birth reduced the extent of the temperature decline, though very few studies determined the effects of these strategies on piglet pre-weaning mortality, and none of these studies combined drying and warming of piglets. There is evidence in the literature to suggest that postnatal piglet temperature may be negatively correlated with blood oxygen level, and may be increased through supplemental oxygen, though there was limited research in this area.

In general, the literature relating to piglet temperature changes after birth is inadequate for developing practical recommendations for piglet management strategies to minimize postnatal temperature decline. In addition, many studies lacked sufficient replication to detect important differences in mortality that would be relevant to commercial producers. Based on the results of this literature review, the main objectives for future research that were identified were to:

- Establish typical changes in piglet rectal temperature over the first 24 h after birth, particularly within the first hour
- Evaluate the effect of:
    - Drying piglets at birth, using varying methods, on piglet rectal temperature
    - Warming piglets at birth using typical commercial practices on piglet rectal temperature
    - Combining warming and drying strategies on piglet rectal temperature
    - Administering oxygen to piglets at birth on piglet rectal temperature
    - Utilizing the most effective strategy for minimizing postnatal rectal temperature decline, on pre-weaning mortality and growth

Tables

Table 1.1a. Study conditions for literature reviewed for the temperature changes of untreated piglets in the early postnatal period.			
Authors	Measurements	Number of animals	Room temperature
Vasdal et al., 2011	Rectal temperature at birth, 2 h, and 24 h after birth	67 litters	20°C until farrowing, 16°C the day after farrowing
Caldara et al., 2014	Thermal imaging at 0, 15, 30, 45, 60, and 120 min after birth	4 litters	26.3°C to 32.5°C
McGinnis et al., 1981	Rectal temperature at 1, 2, 3, 4, 5, 6, 7, and 8 h and 1, 2, and 5 d after birth	326 piglets	22°C
Pedersen et al., 2016	Rectal temperature at birth and every 10 min to 2 h after birth	150 piglets	20.9°C
Pomeroy, 1953	Rectal temperature 2 to 3 min before birth, 18 times from birth through 2 h after birth, and at 16 h	81 piglets	56 F (13.3°C)
Xiong et al., 2018	Rectal temperatures at 0, 15, 30, 45, 60, 90, 120, 180, 240 min and 24 h after birth	99 piglets	23°C
Pattison et al., 1990	Investigation 1: Rectal temperature every 10 min to 60 min, hourly to 36 h	164 piglets	21.4°C
	Investigation 2: Rectal temperature every 30 min to 120 min, at 3 to 7 h and 7 to 10 h	88 piglets	
Andersen and Pedersen, 2015	Rectal temperature at 15, 30, 60, 120, 180, 240 min after birth and 720, 840 and 1440 min after birth of first piglet	36 litters	20°C
Dividich and Noblet, 1981	Rectal temperatures at <1 min, 20 min, and 10 min before 1st, 2nd, 3rd, 6th, 11th, and last suckling	95 piglets	18 to 20°C
Kammersgaard et al., 2011	Rectal temperature at birth and 2 h	635 piglets	18 to 20°C
Vila, 2013	Rectal temperature at 1, 24, and 48 h after birth	19 litters	-
Tuchscherer et al., 2000	Rectal temperature at birth and 1 h after birth	1024 live-born piglets	
Cooper et al., 2018	Rectal temperature at 0, 15, 30, 45, 60, 90, 120, 180, 240, and 1440 min after birth	26 litters	-
Santiago et al., 2019	Thermal imaging at birth, time piglet was dry, time of first colostrum, and 24 h after birth	30 litters, data from first 14 piglets/litter	26°C

Table 1.1b. Study results of literature reviewed for the temperature changes of untreated piglets in the early postnatal period.

Authors	Treatment	Average piglet weight, kg	Temperature at birth, °C	Minimum temperature, °C	Time of minimum temperature	Maximum recovery temperature within 24 h, °C	Time of maximum recovery temperature	Comments
Vasdal et al., 2011	Control (no treatment)	1.5	37.8[a]	36.8[a]	2 h	37.7	24 h	Drying with straw and paper towels
	Creep (piglets placed in creep area)	1.5	37.9[a]	37.1[b]	2 h	37.7	24 h	
	Udder (piglets placed at the udder)	1.4	38.0[b]	37.1[b]	2 h	37.9	24 h	
	Dry (piglets dried and placed back where found)	1.4	37.1[a]	36.6[a]	2 h	37.5	24 h	
	DryCreep (piglets dried and placed in the creep area)	1.5	37.8[a]	37.1[a]	2 h	37.8	24 h	
	DryUdd (piglets dried and placed at the udder)	1.4	38.0[b]	37.4[b]	2 h	37.7	24 h	
McGinnis et al., 1981	2x2x2 factorial:	Males 1.29 Females 1.22	-					Superscript "a" indicates treatment effects ($P \leq 0.05$) Superscript "b" indicates treatment effects ($P \leq 0.01$)
	Floor temperature							
	20°C			37.5	1 h	38.8[a]	24 h	
	30°C			37.6	1 h	39.0[a]	24 h	
	Supplemental heat							
	Heat lamp (temperature under lamp 45°C)			37.5	1 h	39.2[a]	24 h	
	Light bulb (no increase in temperature)			37.5	1 h	38.7[a]	24 h	
	Drying							
	With paper towels			37.9[b]	1 h	38.9	24 h	
	No drying			37.4[b]	1 h	39.0	24 h	
Pedersen et al., 2016	Control on solid floor	1.400	Not individually reported, between 37.9 and 38.7, estimated	34.0[a]	-	35.3[a]	2 h	
	Control on slatted floor	1.319		34.8[ab]		36.4[b]	2 h	
	In-floor heating	1.467		35.9[c]		37.0[b]	2 h	
	Radiant floor plate on solid floor	1.410		35.3[bc]		36.4[b]	2 h	
	Radiant heat above solid floor	1.542		35.4[bc]		36.5[b]	2 h	
	Radiant heat above slatted floor	1.403		36.0[c]		37.1[b]	2 h	
	Straw on a solid floor	1.629		35.9[bc]		37.1[b]	2 h	

[a,b,c]Unless otherwise noted in Comments, means within a study and time with differing superscripts differ at ($P \leq 0.05$).

Table 1.1c. Study results of literature reviewed for the temperature changes of untreated piglets in the early postnatal period.

Authors	Treatment	Average piglet weight, kg	Temperature at birth, °C	Minimum temperature, °C	Time of minimum temperature	Maximum recovery temperature within 24 h, °C	Time of maximum recovery temperature	Comments
Pomeroy, 1953	No treatment, variation in temperature decline for two piglets	-	40.5[1]	37.8 to 38.3[1]	80 to 90 min	38.9[1]	16 h	Detailed piglet temperatures only reported for two representative piglets
Xiong et al., 2018	No treatments	1.47	38.7	33.6	30 min	38.7	24 h	
Pattison et al., 1990	Investigation 1: No treatments	1.390	39.02	35.57	30 min	38.5[1]	24 h	
	Investigation 2:							
	Control	1.567	39.21	36.64	30 min	38.6	7 to 10 h	
	Suckled for 15 min then placed in heated creep area for 45 min	1.458	39.24	36.28	30 min	38.8	7 to 10 h	
Andersen and Pedersen, 2015	Control	1.226	-	34.3[b]	30 min	38.3	840 min	
	Heat (2 infrared heating panels mounted on the back wall of pen)			34.9[a]	30 min	38.2	1440 min	
Dividich and Noblet, 1981	Warm group: concrete flooring with 5 cm straw, two heat lamps for a floor temperature of 30 to 32°C	1.135	40.1[1]	38.8[1]	30 min	39.2[1]	15 h	
	Cold group: concrete flooring without straw, no heat lamps, floor temperature of 18 to 20 °C	1.133	40.1[1]	37.2[1]	30 min	38.5[1]	15 h	
Kammersgaard et al., 2011	Farrowing crate	-	Not reported, range 37 to 41.5°C	77.9% of piglets ≥ 37.0°C; 18.8% < 32°C	2 h	77.9% of piglets ≥ 37.0°C; 18.8% < 32°C	2 h	Birth weight was the best predictor of temperature 2 h after birth
	Loose-housed farrowing				2 h		2 h	

[a,b]Means within a study and time with differing superscripts differ at ($P \leq 0.05$).

[1]Temperatures were estimated from graphical presentation of data.

Table 1.1d. Study results of literature reviewed for the temperature changes of untreated piglets in the early postnatal period.

Authors	Treatment	Average piglet weight, kg	Temperature at birth, °C	Minimum temperature, °C	Time of minimum temperature	Maximum recovery temperature within 24 h, °C	Time of maximum recovery temperature	Comments
Vila, 2013	Sow gestation housing:							
	Pen (lose housed in groups of 9)	1.43	-	37.0^{b}	60 min	38.3^{b}	24 h	
	Stall (individually housed)	1.23	-	38.1^{a}	60 min	38.6^{a}	24 h	
Tuchscherer et al., 2000	Piglets surviving to 10 d of age	Used as a covariate for piglet temperature	38.90	38.4	60 min	-	-	
	Piglets died before 10 d of age		38.97	37.5	60 min	-	-	
Cooper et al., 2018	Drying with a desiccant	1.49	39.2, no treatment effects	2.4 treatment difference, $P \leq 0.05$	45 min (time of greatest temperature difference, $P \leq 0.05$)	No treatment effects, $P > 0.05$	240 and 1440 min	Drying reduced temperature decline for all birth weight quartiles between 15 and 180 min after birth
	Undried Control							
	Birth weight quartile 1	1.13	39.2	35.4^{b}	30 min	38.6	1440 min	
	Birth weight quartile 2	1.43	39.2	36.2^{a}	30 min	38.6	1440 min	
	Birth weight quartile 3	1.62	39.2	36.6^{a}	30 min	38.7	1440 min	
	Birth weight quartile 4	1.81	39.3	36.6^{a}	30 min	38.7	1440 min	
Santiago et al., 2019	Vitality score							Temperatures and birth weights from 2nd-5th parity sows
	Low	1.42733	35.23^{b}	32.16^{b}	Time piglet was dry	37.0^{b}	24 h	
	Medium	1.48901	35.64^{b}	32.33^{b}		37.5^{a}	24 h	
	High	1.53796	36.30^{a}	34.56^{a}		37.7^{a}	24 h	
Caldara et al., 2014	Birth weight < 1.00, 1.00 to 1.39, or ≥ 1.40 kg	1.32	35.94	35.82	15 min	37.37	2 h	Slopes for the relationship between birth weight and surface temperature were significant ($P \leq 0.05$) at 30 and 45 min (0.481 and 0.473°C/kg, respectively)

^{a,b}Means within a study and time with differing superscripts differ at ($P \leq 0.05$).

Table 1.2a. Study conditions for literature reviewed for the effect of birth weight on temperature changes of piglets in the early postnatal period.			
Authors	Measurement method	Number of animals	Room temperature
Caldara et al., 2014	Thermal imaging at 0, 15, 30, 45, 60, and 120 min after birth	4 litters	26.3°C to 32.5°C
Dividich and Noblet, 1981	Rectal temperatures at <1 min, 20 min, and 10 min before 1st, 2nd, 3rd, 6th, 11th, and last suckling	95 piglets	18 to 20°C
Kammersgaard et al., 2011	Rectal temperature at birth and 2 h	635 piglets	18 to 20°C
Pedersen et al., 2016	Rectal temperature at birth and every 10 min to 2 h after birth	150 piglets	20.9°C
Pattison et al., 1990	Rectal temperature every 10 min to 60 min, hourly to 36 h	164 piglets	21.4°C
Andersen and Pedersen, 2015	Rectal temperature at 15, 30, 60, 120, 180, 240 min after birth and 720, 840 and 1440 min after birth of first piglet	36 litters	20°C
Cooper et al., 2019	Rectal temperature at 0, 15, 30, 45, 60, 90, 120, 180, 240, and 1440 min after birth	26 litters	-
Berbigier et al., 1978	Rectal and skin temperature within the first hour of life	100 piglets	-
Santiago et al., 2019	Thermal imaging at birth, time piglet was dry, time of first colostrum, and 24 h after birth	30 litters, data from first 14 piglets/litter	26°C

Table 1.2b. Study results for literature reviewed for the effect of birth weight on temperature changes of piglets in the early postnatal period.

Authors	Treatment	Average piglet weight, kg	Temperature at birth, °C	Minimum temperature, °C	Time of minimum temperature	Maximum recovery temperature within 24 h, °C	Time of maximum recovery temperature	Comments			
Caldara et al., 2014	Birth weight < 1.00, 1.00 to 1.39, or ≥ 1.40 kg	1.32	35.94	35.82	15 min	37.37	2 h	Slopes for the relationship between birth weight and surface temperature were significant ($P \leq 0.05$) at 30 and 45 min (0.481 and 0.473°C/kg, respectively)			
Dividich and Noblet, 1981	Warm group: concrete floor with 5 cm straw, two heat lamps (floor temperature 30 to 32°C)	1.135	40.1[1]	38.8[1]	30 min	39.2[1]	15 h	The percentage of variation in rectal temperature explained by piglet birth weight was 76, 63, 50, 31, and 25% ($P \leq 0.01$) for 0.3, 2, 2.85, 4, and 8.2 h after birth. This was reduced to 5.5% ($P \leq 0.10$) at 14.9 h after birth			
	Cold group: concrete floor, no straw, no heat lamps (floor temperature 18 to 20°C)	1.133	40.1[1]	37.2[1]	30 min	38.5[1]	15 h				
	Loose-housed farrowing				2 h		2 h				
Pedersen et al., 2016								Average rectal temperature by birth weight, superscripts indicate treatment effect within weight: 25th percentile (1.176 kg)	50th percentile (1.396 kg)	75th percentile (1.651 kg)	Birth weight P-value
	Control, solid floor	1.400	Not individually reported, between 37.9 and 38.7°C, estimated from graphical presentation of data	34.0^{a}	-	35.3^{a}	2 h	34.8^{a}	35.4^{a}	36.2^{a}	< 0.01
	Control, slatted floor	1.319		34.8^{ab}		36.4^{b}	2 h	35.5^{b}	36.0^{ab}	36.2^{a}	< 0.0001
	In-floor heating	1.467		35.9^{c}		37.0^{b}	2 h	35.9^{bc}	36.4^{bc}	36.8^{ab}	< 0.001
	Radiant floor plate, solid floor	1.410		35.3^{bc}		36.4^{b}	2 h	36.5^{cd}	36.8^{cd}	37.1^{bc}	> 0.05
	Radiant heat, solid floor	1.542		35.4^{bc}		36.5^{b}	2 h	37.2^{d}	37.3^{d}	37.4^{c}	> 0.05
	Radiant heat, slatted floor	1.403		36.0^{c}		37.1^{b}	2 h	36.7^{cd}	36.8^{d}	37.3^{bc}	< 0.05
	Straw, solid floor	1.629		35.9^{bc}		37.1^{b}	2 h	37.4^{d}	37.4^{d}	37.4^{bc}	> 0.05

^{a,b,c,d}Means within a study and time with differing superscripts differ at ($P \leq 0.05$).

[1]Temperatures were estimated from graphical presentation of data.

Table 1.2c. Study results for literature reviewed for the effect of birth weight on temperature changes of piglets in the early postnatal period.

Authors	Treatment	Average piglet weight, kg	Temperature at birth, °C	Minimum temperature, °C	Time of minimum temperature	Maximum recovery temperature within 24 h, °C	Time of maximum recovery temperature	Comments
Kammersgaard et al., 2011	Farrowing crate	-	Range 37 to 41.5°C	77.9% of piglets ≥ 37.0°C; 18.8% < 32°C	2 h	77.9% of piglets ≥ 37.0°C; 18.8% < 32°C	2 h	Birth weight best predictor of rectal temperature at 2 h after birth
	Loose-housed farrowing				2 h		2 h	
Pattison et al., 1990	No treatments	> 1.500	39.0	36.2	30 min	38.6	24 h	Temperatures estimated from graphical presentation of the data.
		1.000 to 1.500	39.0	35.5	30 min	38.5	24 h	
		< 1.000	39.0	33.9	30 min	37.9	24 h	
Andersen and Pedersen, 2015	Control	1.226	-	34.3^{b}	30 min	38.3	840 min	Slopes for the relationship between birth weight and temperature were significant ($P \leq 0.05$) at all times, highest (0.31 to 0.39) between 15 and 60 min, and decreased to 0.07 by 1440 min.
	Heat (2 infrared heating panels mounted on the back wall of pen)			34.9^{a}	30 min	38.2	1440 min	
Cooper et al., 2019	Drying with a desiccant	1.49	39.2°C, no treatment effects ($P > 0.05$)	2.4°C treatment difference ($P \leq 0.05$)	45 min	No treatment effects ($P > 0.05$)	240 and 1440 min	Drying reduced ($P \leq 0.05$) temperature decline for all birth weight quartiles between 15 and 180 min after birth
	Undried Control							
	Birth weight quartile 1	1.13	39.2	35.4^{b}	30 min	38.6	1440 min	
	Birth weight quartile 2	1.43	39.2	36.2^{a}	30 min	38.6	1440 min	
	Birth weight quartile 3	1.62	39.2	36.6^{a}	30 min	38.7	1440 min	
	Birth weight quartile 4	1.81	39.3	36.6^{a}	30 min	38.7	1440 min	
Berbigier et al., 1978	Drying at birth	-	-	Minimum temperatures were higher ($P \leq 0.01$) for dried piglets				
	Birth weight			Lighter piglets had lower ($P \leq 0.01$) birth and minimum temperatures				
	Air temperature			The difference between air and skin temperature decreased as air temperature increased, and stabilized ~35 to 36°C				
Santiago et al., 2019	Vitality score				Time piglet was dry			
	Low	1.42733	35.23^{b}	32.16^{b}		37.0^{b}	24 h	
	Medium	1.489.01	35.64^{b}	32.33^{b}		37.5^{a}	24 h	
	High	1.53796	36.30^{a}	34.56^{a}		37.7^{a}	24 h	

^{a,b}Means within a study and time with differing superscripts differ at ($P \leq 0.05$).

Table 1.3a. Study conditions for literature reviewed for the effect of drying on temperature changes of piglets in the early postnatal period.

Authors	Measurement method	Number of animals	Room temperature
Vasdal et al., 2011	Rectal temperature at birth, 2 h, and 24 h after birth	67 litters	20°C until farrowing, 16°C the day after farrowing
McGinnis et al., 1981	Rectal temperature at 1, 2, 3, 4, 5, 6, 7, and 8 h and 1, 2, and 5 d after birth	326 piglets	22°C
Pasca et al., 2008	Rectal temperature at 1, 3, 6, 12, 24, 48 h after birth	12 litters	-
Berbigier et al., 1978	Rectal and skin temperature within the first hour of life	100 piglets	-
Christison et al., 1997	Time to udder contact, time to first suckling, average daily gain, and mortality	98 litters	-
Cooper et al., 2019	Rectal temperature at 0, 15, 30, 45, 60, 90, 120, 180, 240, and 1440 min after birth	26 litters	-

Table 1.3b. Results for literature reviewed for the effect of drying on temperature changes of piglets in the early postnatal period.								
Authors	Treatment	Average piglet weight, kg	Temperature at birth, °C	Minimum temperature, °C	Time of minimum temperature	Maximum recovery temperature within 24 h, °C	Time of maximum recovery temperature	Comments
Vasdal et al., 2011	Control (no treatment)	1.5	37.8[a]	36.8[a]	2 h	37.7	24 h	Drying was with both straw and paper towels
	Creep (piglets placed in creep area)	1.5	37.9[a]	37.1[b]	2 h	37.7	24 h	
	Udder (piglets placed at the udder)	1.4	38.0[b]	37.1[b]	2 h	37.9	24 h	
	Dry (piglets dried and placed back where found)	1.4	37.1[a]	36.6[a]	2 h	37.5	24 h	
	DryCreep (piglets dried and placed in the creep area)	1.5	37.8[a]	37.1[a]	2 h	37.8	24 h	
	DryUdd (piglets dried and placed at the udder)	1.4	38.0[b]	37.4[b]	2 h	37.7	24 h	
McGinnis et al., 1981	2x2x2 factorial:	Males 1.29, females 1.22	-					Superscript "a" indicates treatment effects ($P \leq 0.05$) Superscript "b" indicates treatment effects ($P \leq 0.01$)
	Floor temperature							
	20°C			37.5	1 h	38.8[a]	24 h	
	30°C			37.6	1 h	39.0[a]	24 h	
	Supplemental heat							
	Heat lamp (temperature under lamp 45°C)			37.5	1 h	39.2[a]	24 h	
	Light bulb (no increase in temperature)			37.5	1 h	38.7[a]	24 h	
	Drying							
	With paper towels			37.9[b]	1 h	38.9	24 h	
	No drying			37.4[b]	1 h	39.0	24 h	
Pasca et al., 2008	Drying with Mistral:	-	36.9 to 38.4					
	Within 1 to 2 min of birth			Decrease of 0.5 to 0.8°C ($P \leq 0.05$)	1 h	Relatively constant, 37.8 to 38.6°C	24 h	
	10 to 15 min after birth			Decrease of 1.1°C ($P \leq 0.05$)	1 h	Increase from 1 h ($P \leq 0.05$) of 0.5°C for piglets > 1.5 kg, other weights decreased or no change	24 h	
[a,b]Unless otherwise indicated in the Comments, means within a study and time with differing superscripts differ at ($P \leq 0.05$).								

Table 1.3c. Results for literature reviewed for the effect of drying on temperature changes of piglets in the early postnatal period.

Authors	Treatment	Average piglet weight, kg	Temperature at birth, °C	Minimum temperature, °C	Time of minimum temperature	Maximum recovery temperature within 24 h, °C	Time of maximum recovery temperature	Comments
Berbigier et al., 1978	Drying at birth	-	-	Minimum temperatures were higher ($P \leq 0.01$) when piglets were dried				
	Birth weight			Lighter piglets had lower ($P \leq 0.01$) birth temperature and minimum temperature				
	Air temperature			The difference between air and skin temperature decreased as air temperature increased, and stabilized ~35 to 36°C				
Christison et al., 1997	Dried with paper towels	1.371	There was no effect ($P > 0.05$) of drying or warming on time to first udder contact or first suckling, or average daily gain to 24 h or 21 d. The total pre-weaning mortality was 6%[b] for the Dried group, 0%[b] for the Warmed group, and 21%[a] for the Control group					
	Warmed under a heat lamp	1.348						
	Control (no treatment)	1.381						
Cooper et al., 2019	Drying with a desiccant	1.49	39.2°C, no treatment effects ($P > 0.05$)	2.4°C treatment difference ($P \leq 0.05$)	45 min	No treatment effects ($P > 0.05$)	240 and 1440 min	Drying reduced ($P \leq 0.05$) temperature decline for all birth weight quartiles between 15 and 180 min after birth
	Undried control							
	Birth weight quartile 1	1.13	39.2	35.4[b]	30 min	38.6	1440 min	
	Birth weight quartile 2	1.43	39.2	36.2[a]	30 min	38.6	1440 min	
	Birth weight quartile 3	1.62	39.2	36.6[a]	30 min	38.7	1440 min	
	Birth weight quartile 4	1.81	39.3	36.6[a]	30 min	38.7	1440 min	

[a,b]Means within a study and time with differing superscripts differ at ($P \leq 0.05$).

Table 1.4a. Study conditions for literature reviewed for the effect of warming on temperature changes of piglets in the early postnatal period.			
Authors	Measurement method	Number of animals	Room temperature
Vasdal et al., 2010	Rectal temperature at birth, 2 h, and 24 h after birth	67 litters	20°C until farrowing, 16°C the day after farrowing
McGinnis et al., 1981	Rectal temperature at 1, 2, 3, 4, 5, 6, 7, and 8 h and 1, 2, and 5 d after birth	326 piglets	22°C
Pedersen et al., 2016	Rectal temperature at birth and every 10 min to 2 h after birth	150 piglets	20.9°C
Pattison et al., 1990	Investigation 1	164 piglets	21.4°C
	Investigation 2	88 piglets	
Andersen and Pedersen, 2015	Rectal temperature at 15, 30, 60, 120, 180, 240 min after birth and 720, 840 and 1440 min after birth of first piglet	36 litters	20°C
Dividich and Noblet, 1981	Rectal temperatures at <1 min, 20 min, and 10 min before 1st, 2nd, 3rd, 6th, 11th, and last suckling	95 piglets	18 to 20°C
Berbigier et al., 1978	Rectal and skin temperature within the first hour of life	100 piglets	-
Pedersen et al., 2015	Rectal temperature at birth, 0.5, 1, 2, 3, 4, 12, 24, and 48 h after birth	61 litters	15, 20, or 25°C
Christison et al., 1997	Time to udder contact, time to first suckling, average daily gain, and mortality	98 litters	-
Ogunbameru et al., 1991	Pre-weaning mortality, weight at birth, 7 d, and 28 d	Experiment 1: 35 litters	18.9°C
		Experiment 2: 140 litters	21.6°C

<table>
<tr><td colspan="9">Table 1.4b. Results for literature reviewed for the effect of warming on temperature changes of piglets in the early postnatal period.</td></tr>
<tr><th>Authors</th><th>Treatment</th><th>Average piglet weight, kg</th><th>Temperature at birth, °C</th><th>Minimum temperature, °C</th><th>Time of minimum temperature</th><th>Maximum recovery temperature within 24 h, °C</th><th>Time of maximum recovery temperature</th><th>Comments</th></tr>
<tr><td rowspan="6">Vasdal et al., 2010</td><td>Control (no treatment)</td><td>1.5</td><td>37.8[a]</td><td>36.8[a]</td><td>2 h</td><td>37.7</td><td>24 h</td><td rowspan="6">Drying with straw and paper towels</td></tr>
<tr><td>Creep (piglets placed in creep area)</td><td>1.5</td><td>37.9[a]</td><td>37.1[b]</td><td>2 h</td><td>37.7</td><td>24 h</td></tr>
<tr><td>Udder (piglets placed at the udder)</td><td>1.4</td><td>38.0[b]</td><td>37.1[b]</td><td>2 h</td><td>37.9</td><td>24 h</td></tr>
<tr><td>Dry (piglets dried, placed back where found)</td><td>1.4</td><td>37.1[a]</td><td>36.6[a]</td><td>2 h</td><td>37.5</td><td>24 h</td></tr>
<tr><td>DryCreep (piglets dried, placed in creep area)</td><td>1.5</td><td>37.8[a]</td><td>37.1[a]</td><td>2 h</td><td>37.8</td><td>24 h</td></tr>
<tr><td>DryUdd (piglets dried, placed at the udder)</td><td>1.4</td><td>38.0[b]</td><td>37.4[b]</td><td>2 h</td><td>37.7</td><td>24 h</td></tr>
<tr><td rowspan="10">McGinnis et al., 1981</td><td>2x2x2 factorial:</td><td rowspan="10">Males 1.29, females 1.22</td><td rowspan="10">-</td><td></td><td></td><td></td><td></td><td rowspan="10">Superscript "a" indicates treatment effects ($P \leq 0.05$). Superscript "b" indicates treatment effects ($P \leq 0.01$)</td></tr>
<tr><td>Floor temperature</td><td></td><td></td><td></td><td></td></tr>
<tr><td>20°C</td><td>37.5</td><td>1 h</td><td>38.8[a]</td><td>24 h</td></tr>
<tr><td>30°C</td><td>37.6</td><td>1 h</td><td>39.0[a]</td><td>24 h</td></tr>
<tr><td>Supplemental heat</td><td></td><td></td><td></td><td></td></tr>
<tr><td>Heat lamp (temperature under lamp 45°C)</td><td>37.5</td><td>1 h</td><td>39.2[a]</td><td>24 h</td></tr>
<tr><td>Light bulb (no increase in temperature)</td><td>37.5</td><td>1 h</td><td>38.7[a]</td><td>24 h</td></tr>
<tr><td>Drying</td><td></td><td></td><td></td><td></td></tr>
<tr><td>With paper towels</td><td>37.9[b]</td><td>1 h</td><td>38.9</td><td>24 h</td></tr>
<tr><td>No drying</td><td>37.4[b]</td><td>1 h</td><td>39.0</td><td>24 h</td></tr>
<tr><td rowspan="7">Pedersen et al., 2016</td><td>Control on solid floor</td><td>1.400</td><td rowspan="7">Not individually reported, between 37.9 and 38.7, estimated</td><td>34.0[a]</td><td rowspan="7">-</td><td>35.3[a]</td><td>2 h</td><td rowspan="7"></td></tr>
<tr><td>Control on slatted floor</td><td>1.319</td><td>34.8[ab]</td><td>36.4[b]</td><td>2 h</td></tr>
<tr><td>In-floor heating</td><td>1.467</td><td>35.9[c]</td><td>37.0[b]</td><td>2 h</td></tr>
<tr><td>Radiant floor plate on solid floor</td><td>1.410</td><td>35.3[bc]</td><td>36.4[b]</td><td>2 h</td></tr>
<tr><td>Radiant heat above solid floor</td><td>1.542</td><td>35.4[bc]</td><td>36.5[b]</td><td>2 h</td></tr>
<tr><td>Radiant heat above slatted floor</td><td>1.403</td><td>36.0[c]</td><td>37.1[b]</td><td>2 h</td></tr>
<tr><td>Straw on a solid floor</td><td>1.629</td><td>35.9[bc]</td><td>37.1[b]</td><td>2 h</td></tr>
<tr><td rowspan="4">Pattison et al., 1990</td><td>Investigation 1: No treatments</td><td>1.390</td><td>39.02</td><td>35.57</td><td>30 min</td><td>38.5[1]</td><td>24 h</td><td rowspan="4"></td></tr>
<tr><td>Investigation 2:</td><td colspan="6"></td></tr>
<tr><td>Control</td><td>1.567</td><td>39.21</td><td>36.64</td><td>30 min</td><td>38.6</td><td>7 to 10 h</td></tr>
<tr><td>Suckled for 15 min then placed in heated creep area for 45 min</td><td>1.458</td><td>39.24</td><td>36.28</td><td>30 min</td><td>38.8</td><td>7 to 10 h</td></tr>
<tr><td colspan="9">[a,b,c]Unless otherwise indicated in the Comments, means within a study and time with differing superscripts differ at ($P \leq 0.05$).</td></tr>
<tr><td colspan="9">[1]Temperatures were estimated from graphical presentation of data.</td></tr>
</table>

Table 1.4c. Results for literature reviewed for the effect of warming on temperature changes of piglets in the early postnatal period.

Authors	Treatment	Average piglet weight, kg	Temperature at birth, °C	Minimum temperature, °C	Time of minimum temperature	Maximum recovery temperature within 24 h, °C	Time of maximum recovery temperature	Comments
Andersen and Pedersen, 2015	Control	1.226	-	34.3^{b}	30 min	38.3	840 min	
	Heat (2 infrared heating panels mounted on the back wall of pen)			34.9^{a}	30 min	38.2	1440 min	
Dividich and Noblet, 1981	Warm group: concrete flooring, 5 cm straw, two heat lamps, floor temperature 30 to 32 °C	1.135	40.1^{1}	38.8^{a}	30 min	39.2^{a,1}	15 h	
	Cold group: concrete flooring, no straw, no heat lamps, floor temperature 18 to 20 °C	1.133	40.1^{1}	37.2^{b}	30 min	38.5^{b,1}	15 h	
Berbigier et al., 1978	Drying at birth	-	-	Minimum temperatures were higher ($P \leq 0.01$) for dried piglets				
	Birth weight			Lighter piglets had lower ($P \leq 0.01$) birth and minimum temperatures				
	Air temperature			The difference between air and skin temperature decreased as air temperature increased, stabilizing ~35 to 36°C				
Pedersen et al., 2015	Room temperature: 15°C, 20°C, 25°C	1.374	-	35.0°C, average daily gain increased by 4.2 g/d per 1°C increase	-	-	-	Rectal temperature was positively correlated ($P \leq 0.05$) with ADG to weaning. Light birth weight piglets (< 10th percentile) grew faster at higher room temperatures, but the opposite was true for heavy birth weight piglets (> 10th percentile)

^{a,b}Means within a study and time with differing superscripts differ at ($P \leq 0.05$).

^{1}Temperatures were estimated from graphical presentation of data.

Table 1.4d. Results for literature reviewed for the effect of warming on temperature changes of piglets in the early postnatal period.

Authors	Treatment	Average piglet weight, kg	Temperature at birth, °C	Minimum temperature, °C	Time of minimum temperature	Maximum recovery temperature within 24 h, °C	Time of maximum recovery temperature	Comments
Christison et al., 1997	Dried with paper towels	1.371	There was no effect ($P > 0.05$) of drying or warming on time to first udder contact (mean 20 min) or first suckling (mean 40 min), average daily gain to 24 h or 21 d. The total pre-weaning mortality was 6%[b] for the dried group, 0%[b] for the warmed group, and 21%[a] for the control					
	Warmed under a heat lamp	1.348						
	Control (no treatment)	1.381						
Ogunbameru et al., 1991	Experiment 1:	-	Piglet survival to weaning (21 d):	Body weight at weaning (21 d):	-	-	-	Temperatures under heating sources averaged ~30 to 32°C
	Two 250W heat lamps (either side of sow)	1.43	89.02%	5.78 kg	-	-	-	
	Three 250W heat lamps (either side of and behind sow)	1.47	86.23%	6.02 kg	-	-	-	
	Experiment 2:	-	Piglet survival to weaning (28 d):	Body weight at weaning (28 d):	-	-	-	
	One 250W heater (one side of sow)	1.91	93.28%	6.98 kg	-	-	-	
	Two 250W heaters (one side and behind sow)	1.86	93.53%	6.96 kg	-	-	-	
	One hover with 100W light bulb	1.82	93.97%	7.08 kg	-	-	-	
	One hover with 100W light bulb + 250W heater behind sow	1.87	93.72%	7.10 kg	-	-	-	

[a,b]Means within a study and time with differing superscripts differ at ($P \leq 0.05$).

Table 1.5a. Study conditions for literature reviewed for the effect of oxygen administration on piglet pre-weaning mortality and temperature changes of in the early postnatal period.			
Authors	Measurement method	Number of animals	Room temperature
Herpin et al., 2001	Rectal temperature at birth, 30 min, and 24 h, pre-weaning mortality (21 d)	20 piglets (9 and 11 per treatment) for piglet temperature, 31 litters for pre-weaning mortality	24°C
Herpin et al., 1996	Rectal temperature at 24 h, piglet mortality at 10 d of age, blood pCO2	11 litters	24°C
Zaleski and Hacker, 1993	Stillbirth rate, piglet vitality score, sow and piglet blood gas concentration	49 sows/litters	-
Panzardi et al., 2012	Piglet rectal temperature at birth and 24 h after birth, piglet mortality in the first 7 d, and piglet blood oxygen saturation at birth	612 piglets	21 to 27°C

Table 1.5b. Results for literature reviewed for the effect of oxygen administration on piglet pre-weaning mortality and temperature changes of in the early postnatal period.

Authors	Treatment	Average piglet weight, kg	Birth temperature, °C	Minimum temperature, °C	Time of minimum temperature	Maximum recovery temperature within 24 h, °C	Time of maximum recovery temperature	Pre-weaning mortality	Comments
Herpin et al., 2001	Control	~1.4	39.4[1]	37.0[b,1]	30 min	38.6[1]	24 h	12.1%	Blood oxygen concentration was higher ($P \leq 0.05$) between 5 and 30 min of age for piglets given supplemental oxygen at birth. Mean comparisons are between treatments overall and within weight category
	< 1.2 kg			37.3[a] for piglets 1.0 to 1.4 kg				31.6%[a]	
	1.2 to 1.6 kg			36.7[b] for piglets 1.4 to 1.8 kg				2.6%	
	> 1.6 kg							12.2%	
	40% oxygen inhalation for 20 min	~1.4	39.3[1]	37.5[a,1]	30 min	38.6[1]	24 h	8.0%	
	< 1.2 kg			37.5 for piglets 1.0 to 1.4 kg				18.8%[b]	
	1.2 to 1.6 kg			37.6 for piglets 1.4 to 1.8 kg				4.3%	
	> 1.6 kg							7.9%	
Herpin et al., 1996	Highly asphyxiated piglets	1.051	-	-	-	36.3[b]	24 h	42.9%	Pre-weaning mortality P = 0.06
	Control	1.313	-	-	-	38.4[a]	24 h	19.4%	Correlation between blood pCO2 and 24 h rectal temperature = -0.26 (P = 0.05)
	Piglets dead by 10 d of age	1.064	-	-	-	36.5[b]	24 h	-	Correlation between birth weight and 24 h rectal temperature = 0.36 (P = 0.001)
	Piglets alive at 10 d of age	1.342	-	-	-	38.6[a]	24 h	-	

[a,b]Means within a study and time with differing superscripts differ at ($P \leq 0.05$).

[1]Temperatures were estimated from graphical presentation of data.

Table 1.5c. Results for literature reviewed for the effect of oxygen administration on piglet pre-weaning mortality and temperature changes of in the early postnatal period.									
Authors	Treatment	Average piglet weight, kg	Birth temperature, °C	Minimum temperature, °C	Time of minimum temperature	Maximum recovery temperature within 24 h, °C	Time of maximum recovery temperature within 24 h	Pre-weaning mortality	Comments
Zaleski and Hacker, 1993	Control	-	Oxygen administration to the sow did not decrease ($P > 0.05$) stillbirth rates or improve piglet vitality scores, however this may be due to an increase in the first farrowing interval. Oxygen administration increased the blood oxygen levels of the sow, but had no effect ($P > 0.05$) on piglet blood oxygen concentration.						
	Oxygen administration to sow								
Panzardi et al., 2012	No treatment, observational	1.518	38.4	-	-	38.4	24 h	-	All mortality data reported is from birth to 7 d of age
	Birth weight:								
	0.490 to 1.270 kg	-	-	-	-	-	-	9.2%	
	1.271 to 1.540 kg	-	-	-	-	-	-	6.4%	
	1.541 to 1.790 kg	-	-	-	-	-	-	3.2%	
	1.791 to 2.750 kg	-	-	-	-	-	-	2.7%	
	Rectal temperature at birth:								
	31.3 to 36.8	-	-	-	-	-	-	8.7%	
	36.9 to 37.9	-	-	-	-	-	-	4.6%	
	38.0 to 38.5	-	-	-	-	-	-	3.2%	
	38.6 to 40.8	-	-	-	-	-	-	4.8%	
	Rectal temperature at 24 h:								
	33.3 to 38.0	-	-	-	-	-	-	10.1%	
	38.1 to 38.5	-	-	-	-	-	-	2.5%	
	38.6 to 38.9	-	-	-	-	-	-	3.5%	
	39.0 to 40.5	-	-	-	-	-	-	2.0%	
	Oxygen saturation, %:								
	10 to 70	-	-	-	-	-	-	5.4%	
	71 to 77	-	-	-	-	-	-	4.4%	
	78 to 83	-	-	-	-	-	-	7.2%	
	84 to 100	-	-	-	-	-	-	4.6%	

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CHAPTER 2: Piglet cross-fostering literature review

Introduction

Cross-fostering is a commercial practice that is commonly used to reduce pre-weaning mortality, particularly for low birth weight piglets. Although cross-fostering can be performed at any time during lactation, it is primarily carried out early after birth, which will be the focus of this review. The primary objective of cross-fostering is to increase pre-weaning growth and survival of piglets by reducing competition within the litter. This is normally achieved by:

- Minimizing the weight variation within litters by forming litters consisting of piglets with similar birth weights
- Adjusting litter size to at or below each sow's number of functional teats
- Equalizing litter size across sows within a contemporary group
- Forming litters with varying numbers of piglets according to piglet birth weight (e.g., smaller litters for lighter piglets)
- Any combination of the above

In practice, there are a significant number of potential approaches to cross-fostering that can be used. However, not all of these approaches have been studied for their effect on piglet pre-weaning growth and survival. In addition, the studies that have been published are often of limited relevance for development of commercial protocols. Most studies have used relatively small numbers of replications and, consequently, do not have the statistical power to detect practically important differences in piglet performance, particularly pre-weaning mortality. Also, many studies were carried out with much smaller litter sizes than are commonly experienced in practice today. Genetic improvement over the past 20 years has resulted in a substantial increase in average litter size, with the total number of piglets born currently being around 15 piglets per litter. In addition, some studies have focused on light birth weight piglets, excluding heavier piglets, making the results of limited application. Other studies have reported retrospective analyses of relatively large commercial datasets. Although such an approach increases replication, the methods used for cross-fostering were generally poorly defined, and may be confounded with other factors. Given this variation in study design and execution, it is not surprising that the historical cross-fostering literature is extremely limited and often contradictory.

Effect of Cross-fostering on Piglet Growth and Survival

Several studies have evaluated the effects of piglet cross-fostering (moving a piglet from its birth sow to another sow during lactation) on piglet performance. However, the methodology used in these studies was highly variable in terms of the timing of cross-fostering during lactation, litter sizes after cross-fostering, and the number or proportions of piglets cross-fostered within a litter. This variation in methodology makes comparison and interpretation of results across studies difficult.

Several studies found no effect of cross-fostering on piglet pre-weaning growth or mortality. Bishop (2011) in a large-scale field study (411 sows in total) compared litters with piglets cross-fostered within 24 h of birth with non-fostered control litters. There was no effect of cross-fostering piglets on piglet weaning weight, however, there was a trend for mortality to be lower for cross-fostered piglets (Table 2.1). In this study, the cross-fostering protocol was not defined, making it difficult to interpret or compare these results with other studies. Neal and Irvin (1991) also showed no effect of cross-fostering on weaning weight (at 42 d of age) or piglet mortality (to 21 d of age). However, in contrast to the results of Bishop (2011), there was a trend for mortality to be lower in the non-cross-fostered treatment. Heim et al. (2012) compared three treatments: litters with no cross-fostered piglets, all cross-fostered piglets, or an equal number of each. There were no effects of cross-fostering on piglet weaning weight or mortality. However, this study reported exceptionally low mortality levels, with 97.2% of piglets surviving to weaning (Table 2.1).

In contrast, several studies showed reduced pre-weaning performance for cross-fostered piglets, though the study protocols varied widely. Giroux et al. (2000), in a study involving only 32 litters, compared three treatments in which cross-fostering was carried out at 6 d of age. Sows on the Control treatment had no cross-fostered piglets (all piglets on their birth sow, no cross-fostered piglets within the litter). The other two treatments involved piglets within the same litters, that were either cross-fostered or not, respectively: Adopted (piglets from within a litter that were cross-fostered, with non-cross-fostered littermates); Resident (piglets from within a litter that remained with their birth sow, with cross-fostered littermates). Cross-fostered piglets had lower ($P \leq 0.05$) weaning weights (at 17 d of age); pre-weaning mortality was not reported. Cecchinato et al. (2008) carried out a retrospective analysis of 1,347 litters representing six years of data from several farms. The authors reported that 46% of piglets were cross-fostered, though specific protocols were not defined. The hazard ratio for pre-weaning (at 28 d of age) mortality was lower when piglets were not cross-fostered compared to when they were (1.00 vs 0.61). Stewart and Diekman (1989) reported that cross-fostering reduced weaning weights but had no effect on pre-weaning mortality. Horrell and Bennett (1981) conducted a study with 20 litters in two treatments: no cross-fostering versus three piglets cross-fostered at 7 d of age. Cross-fostered piglets had reduced weight gain between 7 and 14 d of age, however weaning weights were not reported.

Kilbride et al. (2014) carried out a survey of 39 outdoor farms involving a total of 855 litter records. The odds ratio for piglet mortality was increased for farms using a low (less than 10% of litters involved) or a high (more than 50% of litters involved) compared to an intermediate (11 to 50% of litters involved) level of cross-fostering. Similarly, odds ratios suggested that likelihood of mortality was lower for litters with ≥ 2 cross-fostered piglets than for those with 0 or 1 piglet cross-fostered. The cross-fostering protocols for the farms were not defined, though these were highly variable between farms. For example, 31% of farms cross-fostered within 24 h of birth, 52% within 71 h, and 17% cross-fostered after 72 h.

Optimum Time for Cross-fostering

In theory, cross-fostering can occur at any time from birth to weaning. However, it is recommended that most cross-fostering should be carried out within 24 h of birth. This allows time for the piglets to obtain colostrum, but is before teat order is established. If fostering takes place before this time then it is generally recommended that the piglets be moved to a sow that has recently farrowed in order to obtain colostrum. A number of studies have shown that cross-fostering after this 24 h period results in a greater disruption to fostered and resident pigs and to the sow (Horrell, 1982; Kilbride et al., 2014). However, few studies have evaluated the effect of time of cross-fostering on piglet pre-weaning growth and mortality.

Only two studies directly evaluated the effect of timing of cross-fostering on piglet pre-weaning growth or mortality. Straw et al. (1998) conducted a retrospective analysis from 300 commercial farms. Farms were classified as carrying out cross-fostering either early (within 3 d of birth) or late (after 3 d). Mortality levels were lower for farms that cross-fostered piglets earlier (Table 2.2). However, the degree of cross-fostering within the early and late cross-fostering farms differed (6.4% and 8.5% of piglets cross-fostered, respectively), making it difficult to separate the effects of timing from the degree of cross-fostering. Kilbride et al. (2014) also surveyed outdoor production farms to determine the effect of timing of cross-fostering. The odds ratio for piglet mortality was lowest for piglets cross-fostered within 24 h, and increased as time from birth to cross-fostering increased to 72 h (Table 2.2).

Due to the low number of studies that directly compared the timing of cross-fostering, studies were also included that only evaluated the effect of cross-fostering but, across studies, used differing times. As discussed above, Bishop (2011), Neal and Irvin (1991), Heim et al. (2012) showed no effect of cross-fostering on pre-weaning mortality or weaning weight when piglets were cross-fostered within 24 h of birth. In contrast, Giroux et al. (2000) and Horrell and Bennett (1981) reported reduced weaning weights when piglets were cross-fostered at 6 and 7 d of age, respectively. Comparing the results across these studies indirectly supports the practice of cross-fostering within the first 24 h after birth.

Effect of Litter Size after Cross-fostering

Although there were several studies that reported on the effects of litter size on piglet pre-weaning growth and mortality, not all of these necessarily used cross-fostering to create the varying litter sizes. In addition, most of these studies are relatively old and, as a result, used litter sizes that are well below current commercial levels. For example, most studies compared litter sizes between 6 and 12 piglets, whereas typical commercial farms currently are producing from 13 to 15 piglets born alive per sow (PigChamp, 2018). In addition, none of these studies related litter size after cross-fostering to the number of functional teats per sow. On average, sows have approximately 14 functional teats and there is no evidence that this number has changed to any extent recently (Rothe, 2011; Charal, 2009; Earnhardt, 2019). Therefore, with historical litter sizes of between 6 and 12 piglets, the number of functional teats was unlikely to limit teat access for piglets in a litter. However, with current litter sizes, the number of functional teats may be an important limitation for piglet performance. In order to develop optimal cross-fostering procedures, it is critical to understand the relationship between functional teat number, litter size, and piglet pre-weaning survival and growth.

A number of studies have evaluated the effect of litter size on piglet pre-weaning growth and mortality, however, results from these studies were highly variable. In addition, many studies used survey data collected from multiple commercial farms, which often have different management protocols; this results in confounding of many of the factors of interest. However, in general, studies found that reducing litter size also reduced piglet pre-weaning mortality and/or improved weaning weights. Zindove (2011) conducted a retrospective analysis on 12 years of farrowing and lactation data (involving a total of 1,836 litters, with no piglet cross-fostering) from a university farm, and reported negative correlations between litter size (which ranged from 3 to 18 piglets born alive) and weaning weight and pre-weaning survival. Similarly, Rohe and Kalm (2000) analyzed five years of data from a university farm (1,338 litters), and reported a positive relationship between increasing litter size (from 9 to 17 total piglets born) and the odds ratios for piglet mortality. Kilbride et al. (2012) carried out a retrospective analysis on the effect of litter size after cross-fostering (< 11, 11, 12, 13, or > 13 piglets) on pre-weaning mortality, utilizing data from 112 farms (both indoor and outdoor production; a total of 2,143 litter records). Piglet mortality was positively related with litter size, with the rate of increase being substantially greater as litter size exceeded 12 piglets (Table 2.3). Stewart and Diekman (1989) compared litters of 6 and ≥ 12 piglets, and found that piglets in the smaller litters had greater weight gain to weaning and lower pre-weaning mortality (Table 2.3). English and Bilkei (2004) evaluated the performance of light birth weight piglets (0.9 to 1.0 kg) in a 2 x

3 factorial arrangement of treatments: litter size [reared in either small (8 piglets) or large (12 piglets) litters]; within-litter birth weight variation [reared with heavy (> 1.6 kg), average (1.2 to 1.59 kg), or other light birth weight piglets]. There was no effect of litter size on piglet weaning weights. However, there was an interaction between litter size and within-litter birth weight variation for pre-weaning mortality. There was no effect of within-litter weight variation for small litters, however for large litters, light piglets had greater pre-weaning mortality when raised with heavy littermates. In a similar study, Deen and Bilkei (2004) evaluated the performance of light birth weight piglets (0.9 to 1.0 kg) in a 2 x 2 factorial arrangement of treatments: litter size [reared in either small (8 piglets) or large (12 piglets) litters]; within-litter birth weight variation [reared with heavy (> 1.6 kg) or average (1.2 to 1.59 kg) birth weight piglets]. There was no effect of litter size on piglet weaning weight. However, there was an interaction between litter size and within-litter birth weight variation for pre-weaning mortality. Light piglets in litters of eight had similar mortality when reared with heavy or average weight littermates. However, in the larger litter size of 12 piglets, light piglets had lower mortality when reared with average than with heavy littermates. These results suggest that the survival of light piglets reared in large litters is negatively related to the weight of littermates. This is most likely the result of increased competition in large litters, and a reduced ability of light birth weight piglets to compete for teat space when reared with heavy littermates. However, this concept requires validation.

Interestingly, three studies showed negative effects of rearing piglets in small litters on pre-weaning mortality. Cecchinato et al. (2008) used hazard ratios for piglet mortality, and reported the lowest risk of piglet mortality for litters of 6 to 11 piglets, with litters with < 6 or ≥ 12 piglets having a higher risk. Similarly, both Kilbride et al. (2014) and Sharpe (1966) estimated odds ratios for piglet mortality in litters of < 9, 9 to 11, or > 11 piglets. Litters with less than 9 piglets or more than 11 piglets had greater odds ratios for mortality than those within this range (Table 2.3).

In conclusion, most studies reported improved piglet pre-weaning survival and growth performance in smaller litter sizes. However, most studies utilized litter sizes that were considerably smaller than would be common with the highly prolific sow lines currently being used in commercial practice. Given this greater numbers of piglets born alive, it is essential that cross-fostering research should focus on effects in the larger litters (i.e., 13 to 15 piglets born alive) which was not the case with historical studies. In addition, there was very little published information on the effect on the potential interactions between litter size and piglet birth weights and cross-fostering practices.

Effect of Variation in Piglet Weight within Litters after Cross-fostering

It has been generally recommended that low birth weight piglets should be the target for cross-fostering because they experience much higher pre-weaning mortality levels than heavier piglets. These light piglets should be better able to compete for teat access when they are reared among piglets of similar weight. However, the published literature on the effects of cross-fostering to reduce within-litter variation in weight on piglet pre-weaning performance is extremely limited. In particular, the effect of creating litters of light piglets on the performance of piglets of all birth weights in the population has not been clearly established. This approach would also result in rearing heavier birth weight piglets in litters of reduced weight variation, and it is not clear how such an approach would affect piglet competition within the litter and, ultimately, piglet pre-weaning performance of the entire population.

Two studies carried out retrospective analyses of farm populations and both suggested a negative relationship between within-litter piglet weight variation at birth and pre-weaning performance. Zindove (2011) analyzed 12 years of data from a university farm (1,788 litters) and reported significant negative correlations between within-litter birth weight variation and both piglet weaning weight and pre-weaning survival. Rohe and Kalm (2000) also analyzed data from a university farm collected over a five-year period (1,338 litters), and reported increasing odds ratios for piglet mortality as the within-litter variation in birth weight increased. Although there are a number of potential confounding factors in these two data sets, the results of these studies suggest that cross-fostering to reduce within-litter variation in weight could potentially improve piglet performance.

Two studies cross-fostered piglets to create litters with differing levels of within-litter birth weight variation. Bierhals et al. (2012) utilized cross-fostering to form 94 litters of 14 piglets each, with three birth weight/variation in birth weight treatments: all light (14 piglets; 1.0 to 1.2 kg), all intermediate (14 piglets; 1.4 to 1.6 kg), or 7 light and 7 intermediate birth weight piglets. There were no significant treatment effects on piglet mortality suggesting that neither birth weight nor within-litter variation in weight affected piglet survival to weaning. In contrast, Huting et al. (2017) found an interaction between piglet birth weight and within-litter birth weight variation for pre-weaning growth and mortality. This study evaluated the performance of light ($\leq$ 1.25 kg) or heavy (1.50 to 2.00 kg) birth weight piglets in litters of uniform (only light or heavy birth weight piglets within a litter) or mixed (equal numbers of light and heavy piglets within a litter) birth weights using a total of 36 litters of 12 piglets. Light birth weight piglets had heavier weaning weights in uniform than in mixed weight litters, with no significant effect of within-litter birth weight variation on pre-weaning mortality. However, light piglets in mixed litters had numerically higher pre-weaning mortality (4 percentage units; $P > 0.05$) than those reared in uniform litters. A difference of this magnitude would be practically important for producers. In contrast to the results for light piglets, heavy birth weight piglets had greater weaning weights and lower pre-weaning mortality in mixed than uniform litters (8.93 kg and 3.9% vs. 7.96 kg and 10.4%, respectively). The results of this study suggest a substantial effect of within-litter variation after cross-fostering on piglet survival and growth depending on piglet birth weight. However, given the small size of this study, further research in this area is needed. One potential reason for the discrepancy between the studies by Bierhals et al. (2012) and Huting et al. (2017) is that the former did not include heavier birth weight piglets (i.e. those > 1.6 kg), which are a significant proportion of most piglet populations, and were also the piglet birth weight group that showed the greatest response to the within-litter weight variation treatment in the latter study.

Some studies have only evaluated the effects of litter birth weight variation on the performance of light birth weight piglets (typically defined as those < 1.0 kg). English and Bilkei (2004) evaluated the performance of light birth weight piglets (0.9 to 1.0 kg) in a 2 x 3 factorial arrangement of treatments: litter size [reared in either small (8 piglets) or large (12 piglets) litters]; within-litter birth weight variation [reared with heavy (> 1.6 kg), average (1.2 to 1.59 kg), or other light birth weight piglets]. For both litter sizes, light piglets had lower weaning weights when reared in litters with heavy than when reared with light or average birth weight piglets. For pre-weaning mortality, there was an interaction between litter size and within-litter birth weight variation. For small litters, there was no effect of within-litter weight variation, however for large litters, light piglets had higher pre-weaning mortality when raised with heavy littermates. In a similar study, Deen and Bilkei (2004) evaluated the performance of light birth weight piglets (0.9 to 1.0 kg) in a 2 x 2 factorial arrangement of treatments: litter size [reared in either small (8 piglets) or large (12 piglets) litters]; within-litter birth weight variation [reared with heavy (> 1.6 kg) or average (1.2 to 1.59 kg) birth weight piglets]. For both litter sizes, light piglets in litters with average birth weight littermates had greater growth rates to weaning than in litters with heavy piglets. There was a significant interaction between litter size and within-litter birth weight variation for pre-weaning mortality. For small litters, there was no effect of within-litter birth weight variation, however light piglets in large litters showed lower pre-weaning mortality when reared in litters with average compared to heavy birth weight piglets. Douglas et al. (2014) evaluated the effects on weaning weight (at 28 d of age) of rearing low (< 1.25 kg) birth weight piglets in litters with either other low weight or "normal" heavier (1.6 to 2.0 kg) weight piglets. Low birth weight piglets reared with heavier piglets had lower weaning weights than those reared with other low birth weight piglets. Piglet pre-weaning mortality was not reported. The results of these studies support the concept that rearing light piglets with heavier littermates reduces pre-weaning growth and increases pre-weaning mortality, especially in larger litters.

Milligan et al. (2001), in a small-scale study involving a total of 53 litters, cross-fostered piglets to evaluate the effect of increased within-litter birth weight variation and litter size on piglet performance. Large (11 to 12 piglets) and small (8 to 9 piglets) litters were formed with either variable birth weights (the lightest and heaviest weight quartiles within a litter), or with uniform birth weights (the two middle weight quartiles within a litter). The average birth weight of the variable and uniform birth weight treatments was similar but the range in weight within these treatments was considerably different. In contrast to most other studies, Milligan et al. (2001) found some evidence for a beneficial effect of increased within-litter variation in birth weight for piglet weight gain in lactation. There was no effect of birth weight variation in small litters; however, for large litters, variable birth weight litters tended ($P \leq 0.10$) to have increased average weight gain to weaning compared to uniform litters. The results for pre-weaning mortality were more complicated. There was no difference between variable and uniform litters for pre-weaning mortality. However, piglets from the lightest quartile, which were in the variable litters, tended ($P = 0.09$) to have the greatest pre-weaning mortality. This suggests that the higher mortality of the lightest piglets was offset by lower mortality of the heaviest piglets (data not reported), resulting in no overall differences between the litter birth weight variation treatments for mortality levels.

In general, the literature relating to the effects of cross-fostering to modify within-litter variation in weight suggested that reduced variation resulted in improved performance overall, and especially for low birth weight piglets. However, the information on the effects of within-litter birth weight variation after cross-fostering on piglet performance is limited, particularly for heavier birth weight piglets.

Conclusion

This literature review has highlighted the need for further research into important factors relating to the development of effective cross-fostering programs for use in commercial practice. It is necessary to validate the effect of cross-fostering practices on pre-weaning piglet performance for a number of areas, including:

- The effect of cross-fostering to reduce within-litter variation in piglet birth weight on the performance of piglets of all birth weights in the population

- Potential interactions between individual piglet weight and litter weight variation for pre-weaning performance to validate the apparently opposite effects observed for light vs. heavy birth weight piglets
- The effects of rearing piglets in litter sizes that are commonly observed in current commercial production
- Potential interactions between litter birth weight variation and litter size

There were also a number of areas that were not addressed by any of the studies reviewed that are important considerations in the development of cross-fostering protocols to maximize piglet pre-weaning performance, including:

- Establishing the effect of cross-fostering *per se* for piglets of all birth weights
- The effect of the number of sources and proportion of piglets cross-fostered within one litter after cross-fostering
- The relationship between cross-fostered litter size and the sow's number of functional teats

However, the literature summarized for the effect of timing of piglet cross-fostering showed consistent results, indicating that the standard protocol of cross-fostering piglets within 12 to 24 h is the optimal approach, and is not a high priority for further research.

Tables

<table>
<tr><td colspan="9">Table 2.1a. Summary of conditions and results for literature reviewed for the effect of cross-fostering on piglet pre-weaning growth performance and mortality.</td></tr>
<tr><td>Authors</td><td>Treatment</td><td>Measurements</td><td>Number of animals</td><td>Litter size</td><td>Average piglet birth weight, kg</td><td>Average piglet weaning weight, kg</td><td>Pre-weaning mortality</td><td>Comments</td></tr>
<tr><td rowspan="3">Giroux et al., 2000</td><td>Adopted- piglet cross-fostered at 6 d of age</td><td rowspan="3">Piglet weight at birth and 6, 17 (weaning), 24, 31, 38, and 45 d of age</td><td rowspan="3">256 piglets</td><td rowspan="3">10 +/- 1</td><td rowspan="3">~1.7</td><td>~5[b]</td><td rowspan="3">-</td><td rowspan="3">Piglets that were cross-fostered at 6 d only gained 76% of the weight gained by non-cross-fostered piglets</td></tr>
<tr><td>Resident- piglet born to the litter with cross-fostered piglet added</td><td>~6[a]</td></tr>
<tr><td>Control- piglet from litter with no cross-fostering</td><td>~6[a]</td></tr>
<tr><td rowspan="2">Bishop, 2011</td><td>Cross-fostered group</td><td rowspan="2">Piglet birth weight within 24 h, weaning weight 2 d before weaning. Piglet mortality</td><td>215 litters</td><td>11.1 +/- 0.26</td><td>1.50</td><td>5.9</td><td>23.4%</td><td>Cross-fostering within 24 h of birth</td></tr>
<tr><td>Non-cross fostered group</td><td>196 litters</td><td>11.7 +/- 0.28</td><td>1.45</td><td>5.9</td><td>25.7%</td><td>Birth weight P-value = 0.07, pre-weaning mortality P-value = 0.08</td></tr>
<tr><td rowspan="2">Cecchinato et al., 2008</td><td>Cross-fostered</td><td rowspan="2">Hazard ratio (HR) for piglet mortality</td><td>7515</td><td rowspan="2">-</td><td rowspan="2">-</td><td rowspan="2">-</td><td>HR 1.00[a]</td><td rowspan="5">Average piglet mortality was 14%</td></tr>
<tr><td>Not cross-fostered</td><td>6409</td><td>HR 0.61[b]</td></tr>
<tr><td rowspan="3">Stewart and Diekman, 1989</td><td>Fostered</td><td rowspan="3">Growth from birth to weaning (21 d), survival rates</td><td rowspan="3">1251 piglets</td><td rowspan="3">6 or 12+</td><td rowspan="3">-</td><td></td><td></td></tr>
<tr><td>No</td><td>6.07 kg gain from birth[a]</td><td>0.17</td></tr>
<tr><td>Yes</td><td>5.86 kg gain from birth[b]</td><td>0.18</td></tr>
<tr><td rowspan="3">Heim et al., 2012</td><td>100% non-fostered</td><td rowspan="3">Piglet weight at d 1, 4, 7, 10, 13, and 16, survival rates</td><td rowspan="3">13 litters/ treatment</td><td rowspan="3">11</td><td>1.462</td><td>5.113</td><td rowspan="3">Overall 97.2% survival, no treatment effects</td><td rowspan="3">Piglets were cross-fostered within 24 h of birth</td></tr>
<tr><td>50/50% fostered and non-fostered</td><td>1.452</td><td>5.129</td></tr>
<tr><td>100% fostered</td><td>1.452</td><td>4.900</td></tr>
<tr><td rowspan="2">Neal and Irvin, 1991</td><td>Cross-fostered</td><td rowspan="2">Survival to 21d, weaning weight</td><td>254 piglets</td><td rowspan="2">8 to 10</td><td>1.43</td><td>10.11</td><td>24.9%</td><td rowspan="2">Mortality P-value ≤ 0.10, but not ≤ 0.05, adjusted for birth vigor. Weaning at 42 d of age</td></tr>
<tr><td>Non cross-fostered</td><td>753 piglets</td><td>1.47</td><td>10.21</td><td>20.1%</td></tr>
<tr><td colspan="9">[a,b]Means within a study and time with differing superscripts differ at ($P \le 0.05$).</td></tr>
</table>

Table 2.1b. Summary of conditions and results for literature reviewed for the effect of cross-fostering on piglet pre-weaning growth performance and mortality.								
Authors	Treatment	Measurements	Number of animals	Litter size	Average piglet birth weight, kg	Average piglet weaning weight, kg	Pre-weaning mortality	Comments
Horrell and Bennett, 1981	Piglets cross-fostered at 7 d	Piglet weights at 3, 7, and 14 d	20 litters	8 to 12	~1.4	1.00 kg gain[b] (7 to 14 d)	-	
	Piglets not cross-fostered					1.27 kg gain[a] (7 to 14 d)		
Kilbride et al., 2014	% of litters with fostering	Odds ratio (OR) for piglet mortality	855 litters	11	-	-		Data from survey of outdoor production farms. Only OR with a P-value < 0.20 were reported
	< 10%						OR 1.00	
	11 to 25%						OR 0.61	
	26 to 50%						OR 0.79	
	> 50%						OR 0.93	
	Number of piglets in litter that were fostered							
	0						OR 1.00	
	1						OR 1.18	
	2						OR 0.80	
	3+						OR 0.92	
[a,b]Means within a study and time with differing superscripts differ at ($P \leq 0.05$).								

Table 2.2. Summary of conditions and results for literature reviewed for the effect of timing of cross-fostering on piglet pre-weaning growth performance and mortality.								
Authors	Treatment	Measurements	Number of animals	Litter size	Average piglet birth weight, kg	Average piglet weaning weight, kg	Pre-weaning mortality	Comments
Giroux et al., 2000	Adopted- piglet cross-fostered at 6 d of age	Piglet weight at birth and 6, 17 (weaning), 24, 31, 38, and 45 d of age	256 piglets	10 +/- 1	~1.70, estimated	~5[b]	-	Piglets that were cross-fostered at 6 d only gained 76% of the weight gained by non cross-fostered piglets
	Resident- piglet born to the litter with cross-fostered piglet added					~6[a]		
	Control- piglet from litter with no cross-fostering					~6[a]		
Bishop, 2011	Cross-fostered group	Piglet birth weight within 24 h, weaning weight 2 d before weaning. Piglet mortality	215 litters	11.1 +/- 0.26	1.50	5.9	23.4%	Cross-fostering within 24 h of birth
	Non-cross fostered group		196 litters	11.7 +/- 0.28	1.45	5.9	25.7%	Birth weight P-value = 0.07, pre-weaning mortality P-value = 0.08
Straw et al., 1998	Early cross-fostering (most piglets moved by 3 d)	Pre-weaning mortality	Survey of 300 farms	10.4	-	-	11.4%[b]	The percentage of piglets cross-fostered differed ($P \leq 0.05$) between timing treatments (6.4 and 8.5% for early and late cross-fostering, respectively)
	Late cross-fostering			10.2			13.5%[a]	
Heim et al., 2012	100% non-fostered	Piglet weight at d 1, 4, 7, 10, 13, and 16, survival rates	13 litters/ treatment	11	1.46	5.113	Overall survival 97.2%, no treatment effects ($P > 0.05$)	Piglets were cross-fostered within 24 h of birth
	50/50% fostered and non-fostered				1.45	5.129		
	100% fostered				1.45	4.900		
Neal and Irvin, 1991	Cross-fostered	Survival to 21d, weaning weight	254 piglets	8 to 10	1.43	10.11	24.9%	Mortality P-value ≤ 0.10, but not ≤ 0.05, adjusted for birth vigor. Weaning at 42 d of age
	Non cross-fostered		753 piglets		1.47	10.21	20.1%	
Horrell and Bennett, 1981	Piglets cross-fostered at 7 d	Piglet weights at 3, 7, and 14 d	20 litters	8 to 12	~1.40	1.00 kg gain[b] (7 to 14 d)	-	
	Piglets not cross-fostered					1.27 kg gain[a] (7 to 14 d)		
Kilbride et al., 2014	Latest fostering of piglets	Odds ratio (OR) for piglet mortality	855 litters	11	-	-		Data from outdoor production farms, survey of farm data. Only OR with a P-value < 0.20 were reported
	< 24 h						OR 1.00	
	25 to 71 h						OR 1.19	
	> 72 h						OR 1.62	
[a,b]Means within a study and time with differing superscripts differ at ($P \leq 0.05$).								

<table>
<tr><td colspan="9">Table 2.3a. Summary of conditions and results for literature reviewed for the effect of litter size on piglet pre-weaning growth performance and mortality.</td></tr>
<tr><td>Authors</td><td>Treatment</td><td>Measurements</td><td>Number of animals</td><td>Litter size</td><td>Average piglet birth weight, kg</td><td>Average piglet weaning weight, kg</td><td>Pre-weaning mortality</td><td>Comments</td></tr>
<tr><td rowspan="6">Cecchinato et al., 2008</td><td>Litter size</td><td rowspan="6">Hazard ratio (HR) for piglet mortality</td><td>300</td><td rowspan="6">-</td><td rowspan="6">-</td><td rowspan="6">-</td><td></td><td rowspan="6">Average piglet mortality was 14%</td></tr>
<tr><td><6</td><td>1246</td><td>HR 3.89^{a}</td></tr>
<tr><td>6 to 8</td><td>6175</td><td>HR 1.16^{bc}</td></tr>
<tr><td>9 to 11</td><td>4696</td><td>HR 1.00^{c}</td></tr>
<tr><td>12 to 14</td><td>1507</td><td>HR 1.40^{b}</td></tr>
<tr><td>>14</td><td></td><td>HR 1.60^{b}</td></tr>
<tr><td rowspan="3">Zindove, 2011</td><td>Litter birth weight variation</td><td rowspan="3">Correlation coefficients (CC) for weaning weight and pre-weaning survival</td><td rowspan="3">1788 litters</td><td rowspan="3">10.21 +/- 2.74</td><td rowspan="3">1.55 +/- 0.33</td><td>CC = -0.13**</td><td>-0.28**</td><td rowspan="3">** Correlation coefficient significantly ($P \leq 0.05$) different from 0</td></tr>
<tr><td>Mean piglet birth weight</td><td>CC = 0.47**</td><td>0.20**</td></tr>
<tr><td>Number born alive</td><td>CC = -0.15**</td><td>-0.21**</td></tr>
<tr><td rowspan="3">Stewart and Diekman, 1989</td><td>Litter size</td><td rowspan="3">Growth from birth to weaning, survival rates</td><td rowspan="3">1251 piglets</td><td></td><td rowspan="3">-</td><td colspan="2"></td><td rowspan="3">Weaning at 21 d of piglet age</td></tr>
<tr><td>6</td><td>6</td><td>6.60 kg gain^{a}</td><td>0.14^{b}</td></tr>
<tr><td>12+</td><td>12+</td><td>5.32 kg gain^{b}</td><td>0.21^{a}</td></tr>
<tr><td rowspan="5">Milligan et al., 2001</td><td>Litter size by litter variation</td><td rowspan="5">Piglet weight on d 0, 3, and 21, piglet survival</td><td rowspan="5">51 litters</td><td colspan="4"></td><td rowspan="5">Litter size: Small- 8 to 9 piglets; Large- 11 to 12 piglets. Litter variation: Variable- Piglets from lightest and heaviest birth weight quartiles; Uniform- Piglets from middle two birth weight quartiles</td></tr>
<tr><td>Small, Variable</td><td></td><td>1.41 kg</td><td>4.57 kg gain</td><td></td></tr>
<tr><td>Large, Variable</td><td></td><td>1.34 kg</td><td>4.40 kg gain</td><td></td></tr>
<tr><td>Small, Uniform</td><td></td><td>1.38 kg</td><td>4.76 kg gain</td><td></td></tr>
<tr><td>Large, Uniform</td><td></td><td>1.33 kg</td><td>3.93 kg gain</td><td></td></tr>
<tr><td rowspan="9">English and Bilkei, 2004</td><td>Low+heavy, small litters</td><td rowspan="9">Pre-weaning mortality and weaning (21 d) weights; only reported for low birth weight piglets</td><td rowspan="9">10 litters/ treatment</td><td>8</td><td rowspan="9">Low- 0.9 to 1 kg; Average- 1.2 to 1.59 kg; Heavy- > 1.6 kg.</td><td>4.9^{b}</td><td>6%^{a}</td><td rowspan="9">Equal numbers of piglets from each birth weight within litter. All piglets cross-fostered within 12 h of birth. Only performance of low birth weight piglets was evaluated</td></tr>
<tr><td>Low+heavy, large litters</td><td>12</td><td>3.4^{c}</td><td>19%^{c}</td></tr>
<tr><td>Low+average, small litters</td><td>8</td><td>5.9^{a}</td><td>7%^{a}</td></tr>
<tr><td>Low+average, large litters</td><td>12</td><td>5.0^{b}</td><td>12%^{b}</td></tr>
<tr><td>Low, small litters</td><td>8</td><td>5.9^{a}</td><td>3%^{a}</td></tr>
<tr><td>Low, large litters</td><td>12</td><td>5.1^{b}</td><td>9%^{b}</td></tr>
<tr><td>Low+heavy, large litters</td><td>12</td><td>2.41 kg gain^{c}</td><td>34.5%^{c}</td></tr>
<tr><td>Low+average, small litters</td><td>8</td><td>4.66 kg gain^{b}</td><td>16.1%^{a}</td></tr>
<tr><td>Low+average, large litters</td><td>12</td><td>3.98 kg gain^{a}</td><td>21.8%^{a}</td></tr>
<tr><td colspan="9">^{a,b,c}Means within a study and time with differing superscripts differ at ($P \leq 0.05$).</td></tr>
</table>

Table 2.3b. Summary of conditions and results for literature reviewed for the effect of litter size on piglet pre-weaning growth performance and mortality.								
Authors	Treatment	Measurements	Number of animals	Litter size	Average piglet birth weight, kg	Average piglet weaning weight, kg	Pre-weaning mortality	Comments
Deen and Bilkei, 2004	Low+heavy, small litters	Low birth weight piglet mortality, weaning (21d) weight	14 litters/ treatment	8	Low: 0.9 to 1 kg; Average: 1.2 to 1.59 kg; Heavy: > 1.6 kg. Equal numbers of piglets from each weight group within litter	3.69 kg gain[a]	19.6%[a]	All piglets cross-fostered within 12 h. Only light birth weight piglets evaluated
	Low+heavy, large litters			12		2.41 kg gain[c]	34.5%[c]	
	Low+average, small litters			8		4.66 kg gain[b]	16.1%[a]	
	Low+average, large litters			12		3.98 kg gain[a]	21.8%[a]	
Kilbride et al., 2014	Litter size after fostering	Odds ratio (OR) for piglet mortality	855 litters	-	-	-		Survey of outdoor production farms. Only OR with a P-value < 0.20 reported
	< 8						OR 2.21	
	8						OR 1.03	
	9						OR 1.00	
	10						OR 1.00	
	11						OR 1.20	
	12+						OR 2.23	
Kilbride et al., 2012	Number of piglets per litter after fostering	Piglet pre-weaning mortality	2143 litters from 112 commercial farms	-	-	-		
	< 11						8.6%	
	11						9.6%	
	12						12.2%	
	13						15.7%	
	> 13						23.3%	
Rohe and Kalm, 2000	Variation of birth weight within litter	Regression of odds ratio (OR) for piglet mortality	1338 litters	10.8	1.556	-	2.2623 (S.E. 0.4530)	Weaned at 21.6 d
	Total number of piglets born						0.0607 (S.E. 0.0207)	
	Litter mean piglet birth weight						Linear: 5.6072. Quadratic: 1.2090 (S.E. 1.4459, 0.4760)	
Sharp, 1966	Litter size	Piglet pre-weaning (6 wk) mortality	53 litters	11.2	-	-		Trend for more uniform (lower variation) litters to have lower mortality rates
	4 to 8						26.3%	
	9 to 11						17.1%	
	12 to 14						24.6%	
	15 to 17						39.2%	
[a,b,c]Means within a study and time with differing superscripts differ at ($P \leq 0.05$).								

Table 2.4a. Summary of conditions and results for literature reviewed for the effect of within-litter birth weight variation on piglet pre-weaning growth performance and mortality.

Authors	Treatment	Measurements	Number of animals	Litter size	Average piglet birth weight, kg	Average piglet weaning weight, kg	Pre-weaning mortality	Comments
Zindove, 2011	Within-litter birth weight variation	Correlation coefficients (CC) with piglet weaning weight and pre-weaning survival	1788 litters	10.21 +/- 2.74	1.55 +/- 0.33	CC = -0.13**	CC = -0.28**	** Correlation coefficients significantly ($P \leq 0.05$) different from 0
	Mean piglet birth weight					CC = 0.47**	CC = 0.20**	
	Number born alive					CC = -0.15**	CC = -0.21**	
Bierhals et al., 2012	14 light piglets (1.0 to 1.2 kg)	Litter weight at cross-fostering and 7, 15, and 19 d, piglet survival at 7 and 19 d	94 litters	14	Litter 15.6 kg^{c}	Litter wt. 64.6 kg	5.8%	All piglets were cross-fostered, between 8 and 24 h after birth
	7 light (1.0 to 1.2 kg) and 7 intermediate (1.4 to 1.6 kg) piglets				Litter 18.4 kg^{b}	Litter wt. 69.3 kg	5.6%	
	14 intermediate (1.4 to 1.6 kg) piglets				Litter 20.9 kg^{a}	Litter wt. 72.2 kg	4.8%	
Milligan et al., 2001a	Litter size by litter variation	Piglet weight on d 0, 3, and 21, piglet survival	51 litters					Litter variation: Variable- Piglets from lightest and heaviest birth weight quartiles; Uniform- Piglets from middle two birth weight quartiles
	Small, Variable			8 to 9	1.41	4.57 kg gain		
	Large, Variable			11 to 12	1.34	4.40 kg gain		
	Small, Uniform			8 to 9	1.38	4.76 kg gain		
	Large, Uniform			11 to 12	1.33	3.93 kg gain		
English and Bilkei, 2004	Low+heavy, small litters	Pre-weaning mortality and weaning (21d) weight for low birth weight piglets only	10 litters/ treatment	8	Low- 0.9 to 1 kg; average- 1.2 to 1.59 kg; heavy- > 1.6 kg. Equal numbers of piglets from each weight group within litter	4.9^{b}	6%^{a}	All piglets cross-fostered within 12 h of birth. Only performance of light birth weight piglets evaluated
	Low+heavy, large litters			12		3.4^{c}	19%^{c}	
	Low+average, small litters			8		5.9^{a}	7%^{a}	
	Low+average, large litters			12		5.0^{b}	12%^{b}	
	Low, small litters			8		5.9^{a}	3%^{a}	
	Low, large litters			12		5.1^{b}	9%^{b}	

^{a,b,c}Means within a study and time with differing superscripts differ at ($P \leq 0.05$).

Table 2.4b. Summary of conditions and results for literature reviewed for the effect of within-litter birth weight variation on piglet pre-weaning growth performance and mortality.

Authors	Treatment	Measurements	Number of animals	Litter size	Average piglet birth weight, kg	Average piglet weaning weight, kg	Pre-weaning mortality	Comments
Deen and Bilkei, 2004	Low+heavy birth weight, small litters	Pre-weaning mortality and weaning (21d) weights of low birth weight piglets only	14 litters/ trt	8	Low: 0.9 to 1kg; Average: 1.2 to 1.59 kg; Heavy: > 1.6 kg. Equal numbers of piglets from each weight group within litter	3.69 kg gain[a]	19.6%[a]	All piglets cross-fostered within 12 h of birth. Only performance of light birth weight piglets evaluated
	Low+heavy birth weight, large litters			12		2.41 kg gain[c]	34.5%[c]	
	Low+average birth weight, small litters			8		4.66 kg gain[b]	16.1%[a]	
	Low+average birth weight, large litters			12		3.98 kg gain[a]	21.8%[a]	
Huting et al., 2017	Light piglets in Uniform litters	Piglet weight at birth and weaning (28 d), piglets removed (morbidity and mortality) to weaning	144 piglets	12	Light: <1.25 kg, Heavy: 1.50 to 2.00 kg	7.37[a]	18.8%[a]	Piglets cross-fostered at birth. Uniform litters had all piglets of the same birth weight group (Light or Heavy). Mixed litters had equal numbers of Light and Heavy piglets. Comparisons for litter composition made within birth weight group
	Heavy piglets in Uniform litters		144 piglets			7.96[b]	10.4%[b]	
	Light piglets in Mixed litters		77 piglets			6.93[b]	23.4%[a]	
	Heavy piglets in Mixed litters		77 piglets			8.93[a]	3.9%[c]	
Douglas et al., 2014	Low birth weight piglets (< 1.25 kg)	Piglet weight at birth and weaning (28 d), average daily gain	67 piglets	11 to 12	1.14	7.13[a]	-	Piglets cross-fostered within 24 h
	Low and normal (1.6 to 2.0 kg) birth weight piglets		66 piglets		1.15	6.87[b]		
Rohe and Kalm, 2000	Variation of birth weight within litter	Regression of odds ratio (OR) for piglet mortality	1338 litters	10.8	1.556	-	2.2623 (S.E. 0.4530)	Weaned at 21.6 d
	Total number of piglets born						0.0607 (S.E. 0.0207)	
	Litter mean piglet birth weight						Linear -5.6072, quadratic 1.2090 (S.E. 1.4459, 0.4760)	

[a,b,c]Means within a study and time with differing superscripts differ at ($P \leq 0.05$).

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CHAPTER 3: Effect of method of drying piglets at birth on rectal temperature over the first 24 h after birth

Abstract

Piglets are born wet, and evaporation of that moisture decreases body temperature, increasing the risk of mortality. The objective of this study was to compare the effect of two commercially-applicable methods for drying piglets at birth on piglet rectal temperature over 24 h after birth. The study was carried out in standard commercial farrowing facilities with 52 litters, using a completely randomized design with three Drying Treatments: Control (not dried); Desiccant (dried at birth using a cellulose-based desiccant); Paper Towel (dried at birth using paper towels). Litters were randomly allotted to treatments at the birth of the first piglet. At birth, piglets were individually identified, and the treatment was applied. Rectal temperature was measured at 0, 10, 20, 30, 45, 60, 120, and 1440 min (24 h) after birth. Data were analyzed using a repeated measures model with PROC MIXED of SAS, with litter as the experimental unit and piglet a subsample of the litter. The model included the fixed effects of treatment and time (as a repeated measure), and the interaction. There was no effect ($P > 0.05$) of treatment on temperature at birth, or 10 or 1440 min after birth. Piglet temperatures between 20 and 120 min after birth were similar ($P > 0.05$) for the Desiccant and Paper Towel treatments, but were greater ($P \leq 0.05$) than the Control. The effect of birth weight on the response to Drying Treatment was evaluated by dividing the data into Light (< 1.0 kg), Medium (1.0 to 1.5 kg), or Heavy (> 1.5 kg) piglet Birth Weight Categories. Piglet rectal temperature data at each measurement time were analyzed using a model that included the fixed effects of Birth Weight Category, Drying Treatment, and the interaction. Temperatures of Light piglets were lower ($P \leq$ 0.05) than those of Heavy piglets between 20 and 120 min after birth, with Medium piglets being

intermediate and generally different to the other two weight categories at these times. The difference in temperature between Light as compared to Medium or Heavy piglets was greater for the Control than the other two Drying Treatments at 60 min after birth. These results suggest that drying piglets at birth is an effective method to reduce rectal temperature decline in the early postnatal period, especially for low birth weight piglets.

Introduction

Pre-weaning mortality is a source of significant economic loss for the U.S. swine sector, a major welfare concern, and presents a negative public image of the industry. According to PigChamp (2019) data, pre-weaning mortality levels have increased on U.S. commercial units over recent years, and currently average approximately 15% of piglets born alive. A major factor associated with this increase is the reduction in average piglet birth weight due to the increase in litter sizes that have occurred in commercial dam lines over a similar time period (PigChamp, 2019). Estimates suggest that approximately 10 to 15% of piglets born are of low birth weight (i.e., weighing < 1 kg) and that mortality in these piglets is extremely high, often exceeding 50% (Feldspausch et al., 2019).

A major pre-disposing factor for pre-weaning mortality is hypothermia in the early postnatal period (Panzardi et al., 2009). All neonatal piglets are highly cold susceptible; they are born with low body fat for insulation and rely on increasing heat production to maintain body temperature (Herpin et al., 2002). In addition, the piglet is born wet and must expend energy (heat) to dry the body surface. Consequently, in the absence of any intervention, all piglets will experience chilling under typical farrowing room conditions (Curtis, 1974), and are more likely to die from hypothermia (Curtis, 1970). In addition, chilled piglets have reduced vigor and are less able to compete during suckling and, consequently, have reduced colostrum intake (Le

Dividich and Noblet, 1981). This reduces the energy intake and immune status of the piglets and predisposes them to dying from other causes, such as starvation, disease, and crushing (Lay et al., 2001; Devillers et al., 2011).

Low birth weight piglets experience the largest postnatal body temperature decline and have the highest levels of pre-weaning mortality (Tuchscherer et al., 2000). They have greater surface area to body volume ratio than heavier birth weight piglets and, therefore, greater potential to lose relatively more heat in a cool environment (Herpin et al., 2002; Baxter et al., 2008; Theil et al., 2014). They also generally have lower body fat for insulation (Curtis, 1974) and lower energy reserves (glycogen and fat) for heat production (Lossec et al., 1998). Consequently, low birth weight piglets experience a greater postnatal temperature decline than heavier littermates, which can pre-dispose them to higher rates of mortality in the early postnatal period (Panzardi et al., 2013). Our understanding of piglet body temperature changes in the postnatal period, other than in a general sense, is extremely limited, especially under typical commercial conditions. Understanding these changes in body temperature and the effectiveness of potential intervention strategies are critical first steps in developing practically applicable approaches to minimizing temperature decline and to reducing associated mortality.

One potential intervention to reduce the extent of piglet temperature decline is to dry piglets at birth. This approach should reduce heat loss due to evaporation of amniotic fluids from the body surface; however, its effectiveness may vary depending on the drying material used. While drying has been used commercially, there is limited published information in the scientific literature either for the effects on postnatal body temperature changes, or on the relative effectiveness of the various approaches that can be used. The objectives of this study were to determine typical changes in piglet body temperature in the early postnatal period and the effect of method of drying piglets at birth on these changes. In addition, the effects of piglet birth weight and the potential interactions with drying method on piglet postnatal temperatures were evaluated.

Materials and Methods

This study was conducted in farrowing facilities of a commercial breed-to-wean farm of The Maschhoffs, LLC, located near Crawfordsville, IN during the months of December and January. The experimental protocol was approved by the University of Illinois Institutional Animal Care and Use Committee prior to the initiation of the research.

Animals, Experimental Design, Treatments, and Allotment

A total of 52 litters (618 piglets) were used in the study. Sows were from commercial dam lines of Yorkshire and Landrace origin (11 lines in total), that had been mated to commercial sire lines. The study used a completely randomized design, with litter as the experimental unit and piglet as a subsample of the litter, to compare three Drying Treatments: Control - no drying; Desiccant - piglets were dried at birth by coating with a commercial cellulose-based desiccant until completely dry; Paper Towel - piglets were dried at birth with paper towels until completely dry. Litters were randomly allotted to treatment at the start of farrowing after the birth of the first piglet, with the restriction that dam genotype and parity were balanced across treatments across the entire study period. Treatments were applied to entire litters to avoid mixing of dried and undried piglets, as amniotic fluids could be transferred between piglets on different treatments, which could affect subsequent temperature changes.

Housing and Management

Sows were housed in individual farrowing crates, each located within a farrowing pen which had either woven metal or perforated plastic flooring. Crate dimensions were 0.55 m by

1.95 m, giving a floor space within the crate of 1.07 m²; pen dimensions were 1.52 m by 2.07 m, providing a total pen floor space of 3.15 m^2. Crates were equipped with a sow-operated feed dispenser attached to the feed trough, and a nipple-type water drinker for the sow. An infrared heat lamp was suspended over an insulated rubber mat located in the center of the floor area on one side of the farrowing pen (average temperature under the heat lamp during the study period was 34.3 ± 3.92°C). Room temperature was maintained using fans and heaters; thermostats were set to 22.5°C throughout the study period.

Management in the farrowing facility was according to unit protocols, which were generally in line with standard commercial practices. Sows that had not farrowed by d 116 of gestation were induced to farrow on the following day using Lutalyse (2 injections of 1 mL given at 0600 and 1200 h; Zoetis; Parsippany, NJ); the identity of each sow induced and date of induction were recorded. The farrowing process was supervised by the investigators; if the interval between the births of piglets exceeded 60 min, the investigator checked the birth canal for obstructions, and assisted the farrowing process as needed.

Procedures and Measurements

Sows were monitored continuously during farrowing. Piglet rectal temperature was measured at birth, and piglets were given a uniquely numbered ear tag for identification. Piglets assigned to the Desiccant and Paper Towel treatments were dried according to treatment; piglets on the Control treatment were not dried. Immediately after these procedures, piglets on all treatments were returned to the farrowing pen. Piglet and sow rectal temperatures were measured using a HSTC-TT-K-24S-36 thermocouple attached via a SMPW-K-M connector to a dual input K/J digital thermometer (HH801A; Omega; Stamford, CT). Piglet temperatures were measured (at a depth of 2.5 cm) at birth, 10, 20, 30, 45, 60, 120, and 1440 min after birth; sow temperature was measured at a depth of 10 cm at the start and end of the farrowing process (defined as no piglets expelled for at least 2 h, no piglets in the birth canal, and passage of placenta). Thermometers were calibrated each week during the study period by taking measurements in a temperature-controlled chamber that was set at temperatures that encompassed the expected range (i.e., 30, 32, 34, 36, 38, and 40°C). Piglets were weighed on the day of birth using a Brecknell LPS-15 bench scale (Avery Weigh-Tronix; Fairmont, MN). Scales were calibrated daily prior to use with a standard test weight.

Farrowing room ambient temperature was measured continuously over the study period using data loggers [Temtop TemLog 20H (Elitech Technology; Silicon Valley, CA)]. Ambient temperatures in each farrowing pen [behind and at either side of the sow (one of these measurements being under the heat lamp)] were measured at the beginning and end of the farrowing process using a digital infrared thermometer [TOOGOO GM320 LCD digital infrared thermometer gun (Shenzhen IMC Digital Technology Co. Shenzhen, China)].

Statistical Analysis

The litter of piglets was the experimental unit for all measurements; piglet was a sub-sample of litter. The PROC UNIVARIATE procedure of SAS (SAS Inst. Inc., Cary, NC) was used to verify normality and homogeneity of variances of the residuals and data were analyzed using the PROC MIXED procedure of SAS (Littell et al., 1996). The study was carried out using a completely randomized design; the model used for the analysis of sow parameters and litter measurements accounted for the fixed effect of Drying Treatment. The model used for analysis for treatment differences in piglet birth weight also included the random effect of piglet within litter. Treatment effects on piglet rectal temperatures at the various measurement times after birth were analyzed using a repeated measures analysis, with the model accounting for the fixed effects of Drying Treatment, measurement time, and the interaction, and the random effect of piglet within litter. A repeated-measures statement was included in the model with measurement time as the REPEATED term and piglet as the SUBJECT term in the SAS statement.

An analysis was carried out to determine if the response to Drying Treatments differed according to piglet birth weight. Data were divided into Light (< 1.0 kg), Medium (1.0 to 1.5 kg), or Heavy (> 1.5 kg) Birth Weight Categories. The maximum weight for the Light category (i.e., 1.0 kg) represented the birth weight below which pre-weaning mortality increases substantially (Zotti et al., 2017). The minimum weight for the Heavy category (i.e., 1.5 kg) represented the weight above which pre-weaning mortality is relatively unaffected by birth weight (Zotti et al., 2017). Piglet rectal temperature data at each measurement time were analyzed using a statistical model that included the fixed effects of Birth Weight Category, Drying Treatment, and the interaction, and the random effect of piglet within litter.

In addition, regression analyses were carried out to determine the effects of piglet birth weight and Drying Treatments on rectal temperature at each time using PROC MIXED. Piglet rectal temperature within time was the dependent variable, and the model included the linear and quadratic effects of birth weight and all interactions with Drying Treatment, and the random effect of sow. Birth weight values were centered before squaring to reduce effects of multicollinearity. A broken-line analysis (with a single slope and plateau) was conducted using PROC NLMIXED for the times that showed a significant quadratic effect of birth weight, including the random effect of sow.

For all analyses, differences between least-squares means were separated using the PDIFF option of SAS, and differences were considered significant at $P \leq 0.05$.

Results and Discussion

A number of sow parameters and ambient temperatures in the farrowing pen are summarized by treatment in Table 3.1. There were no differences ($P > 0.05$) between Drying Treatments for any of these parameters or measurements. Sow temperatures before and after farrowing were between 37 and 40°C, which is typical for farrowing sows (Littledike et al., 1979). Temperatures within the farrowing pens (average between 21.1 and 22.1°C) were close to the thermostat set point for the farrowing rooms (22.5°C). Litter sizes and piglet birth weights are summarized by treatment in Table 3.2. In general, the sows and litters used in the study were typical of commercial production in the U.S. The average number of piglets born alive per litter (11.5 to 12.4) was similar to that for U.S. herds reported by PigChamp at the time this study was carried out (13.2 piglets per sow; 2017, 2018). Average piglet weights (1.41 to 1.44 kg) were similar to those reported in recent commercial studies (e.g. Vasdal et al., 2011; Feldspausch et al., 2019).

Temperature Decline of Untreated Piglets

Piglet rectal temperatures for the three Drying Treatments from birth to 1440 min after birth are presented in Table 3.2. As expected, temperatures at birth, which were approximately 39°C, were similar ($P > 0.05$) across all treatments. There is considerable variation between published studies in values for piglet rectal temperature at birth, ranging from 37.8°C (Vasdal et al., 2011) to 40.5°C (Pomeroy, 1953). In addition, Kammersgaard et al. (2011) reported considerable variation in birth temperatures within the same study (37.0 to 41.5°C). Given that piglet temperature declines rapidly immediately after birth (Pattison et al., 1990), differences between studies may be mainly due to the timing of measurement relative to the time of birth.

The temperature decline of the untreated Control piglets provides an estimate of temperature changes that piglets experienced under standard commercial conditions without any intervention. Control piglets experienced an extensive decline in rectal temperature, reaching a minimum (3.5°C lower than at birth) at 30 min (Table 3.2). There is considerable variation between studies in the time after birth of and value for the minimum temperature in untreated piglets. In part, this reflects differences in the timing of the first postnatal temperature measurement. In some studies, this was not until 1 h after birth (McGinnis et al., 1981; Tuchscherer et al., 2000; Vila, 2013) and, consequently, the time of the actual minimum temperature was probably missed. Caldara et al. (2014) found that the minimum body surface temperature was reached at 15 min after birth. However, similar to the current experiment, a number of studies have found that the minimum temperature occurred at 30 min after birth (Pattison et al., 1990; Andersen and Pedersen, 2015; Xiong et al., 2018; Cooper et al., 2019). There was considerable variation in the estimates of minimum temperatures between these studies, ranging from 33.6°C (Xiong et al., 2018) to 36.6°C (Pattison et al., 1990). Variation between studies in the extent of temperature decline in untreated piglets after birth may be due in part to differences in methodology. For example, measuring body surface temperature using thermal imaging (Caldara et al., 2014) compared to measurement of rectal temperature (e.g. Cooper et al., 2019). In addition, other parameters varied between studies, such as piglet birth weight (e.g. 1.2 kg, Andersen and Pedersen, 2015 compared to 1.5 kg Cooper et al., 2019) and room temperature (e.g. 18 to 20°C, Kammersgaard et al., 2011 compared to 23°C, Xiong et al., 2018). Despite these differences, the overall conclusion from this and previous research is that all piglets experience a large temperature decline in the early postnatal period.

Subsequent to 30 min after birth, the temperature of the Control piglets increased at all measurement times and by 1440 min approached that observed at birth (Table 3.2). In agreement, most studies have shown that piglet temperatures approach those observed at birth by 24 h after birth (e.g. Vila, 2013; Xiong et al., 2018; Cooper et al., 2019). These results suggest that, on average, piglets recover from the dramatic early postnatal decrease in temperature and reach normal levels by the end of the first day of life.

Effects of Drying Method

The effects of drying method on piglet rectal temperature over the first 1440 min after birth are presented in Table 3.2, and differences in temperature between the Control and the other two Drying Treatments at each measurement time between 0 and 120 min after birth are illustrated in Figure 3.1. These measurement times have been chosen to focus on the period when the greatest changes in rectal temperature occurred (i.e., the first 2 h after birth). There was no effect of Drying Treatment on piglet temperatures at 0, 10, or 1440 min after birth (Table 3.2; $P > 0.05$). However, between 20 and 120 min after birth, piglets on the Desiccant and Paper Towel treatments had greater rectal temperatures ($P \leq 0.05$) than those on the Control (Table 3.2). There were no differences ($P > 0.05$) between the Desiccant and Paper Towel treatments at any measurement time.

In agreement with other studies (Berbigier et al., 1978; Vasdal al., 2011; Cooper et al., 2019), the current experiment found no effect of Drying Treatment on temperatures at birth, which was expected given that these measurements were taken before the treatments were applied. Minimum temperatures were reached earlier for the Desiccant and Paper Towel treatments (20 min; 36.7 and 36.4°C, respectively) than for the Control (30 min; 35.6°C; Table 3.2). Relatively few studies measured temperatures frequently enough to compare the timing of minimum temperatures between dried and undried piglets. Berbigier et al. (1978) and Cooper et al. (2019) measured temperatures relatively frequently in the early postnatal period, however, both studies reported treatment differences rather than mean temperatures at each time.

In the current study, the maximum difference between dried and undried Control piglets occurred at 1 h after birth (+1.1°C and +1.4°C for the Paper Towel and Desiccant treatments, respectively; Figure 3.1). This timing is similar to a number of other reports (Berbigier et al.; 1978; McGinnis et al., 1981; Cooper et al., 2019), which found the greatest differences in rectal temperature between dried and undried piglets was between 30 and 60 min after birth. However, for these studies, the temperature difference between dried and undried piglets varied, ranging from +0.5°C for piglets dried with paper towels in the study of McGinnis et al. (1981) to +2.4°C for piglets dried with a desiccant in the study of Cooper et al. (2019). Cooper et al. (2019) used similar methodology and conditions as the current study, and the difference in the response to the desiccant treatment in these studies was surprising and warrants further investigation. In general, the results of the current and previous studies suggest that drying (with either a desiccant or paper towels) is effective at reducing both the extent and duration of postnatal temperature decline.

Effect of Birth Weight on Responses to Drying

The least-squares means for the Drying Treatment by Birth Weight Category interaction sub-classes for piglet rectal temperature at each measurement time are presented in Table 3.3. There was no treatment interaction ($P > 0.05$) for temperature at birth, which is in agreement with most studies (Pattison et al., 1990; Caldara et al., 2014; Cooper et al., 2019). There were Drying Treatment by Birth Weight Category interactions ($P \leq 0.05$) for temperatures at all measurement times between 10 and 1440 min after birth (Table 3.3).

In general, the differences between birth weight categories followed a similar pattern over time within each Drying Treatment. At all measurement times between 10 and 120 min, Light piglets had lower ($P \leq 0.05$) temperatures than Heavy piglets, and Medium piglets were generally intermediate and different ($P \leq 0.05$) to the other two weight categories (Table 3.3). The exceptions to this were at 10 min for all three Drying Treatments, and at 60 and 120 min for the Desiccant treatment, when Medium and Heavy piglets had similar ($P > 0.05$) temperatures. Cooper et al. (2019) also showed that piglets in the lightest birth weight quartile (mean birth weight of 1.13 kg) had temperatures 30 min after birth that were between 0.8 and 1.2°C lower than those in the three heavier weight quartiles (1.43, 1.62, and 1.81 kg, respectively). Similarly, Pedersen et al. (2016) found that rectal temperature at 2 h after birth in undried piglets increased (35.5, 36.0, and 36.2°C) with increasing birth weight (1.18, 1.40, 1.65 kg, respectively). In addition, Pattison et al. (1990) found that piglets with birth weights below 1 kg had lower minimum rectal temperatures (which occurred at 30 min after birth) by 1.6 and 2.3°C compared to piglets with birth weights of 1.0 to 1.5 kg, or > 1.5 kg, respectively.

Birth weight effects were relatively small (≤ 0.9°C; Table 3.3) for all treatments at 1440 min after birth; however, Light piglets on the Control, but not the other two Drying Treatments, continued to have lower ($P \leq 0.05$) temperatures than heavier littermates (Table 3.3). Most other studies have also reported that birth weight effects decreased over the first 24 h after birth. Le Dividich and Noblet (1981) found that the percentage of variation in rectal temperature explained by birth weight was high in the early postnatal period (76% at 20 min after birth) but had decreased to less than 5% by 15 h after birth. The results of the current study are in general agreement with this finding, nevertheless, light birth weight piglets continued to have lower temperatures than heavier littermates at 24 h after birth.

Although the general pattern of temperature decline was relatively similar for the three Birth Weight Categories across the three Drying Treatments, the difference between Birth Weight Categories was greater within the Control than within the other treatments. For example, for the Control treatment, the minimum temperature of Light compared to Medium and Heavy piglets occurred later (at 60, 30, and 30 min, respectively) and was lower (33.4, 35.4, and 36.3°C, respectively; Table 3.3). In contrast, for the Desiccant and Paper Towel treatments, the minimum temperature occurred at a similar time for the three Birth Weight Categories (30, 20, and 30 min, respectively) and the differences between Birth Weight Categories was relatively small (35.5, 36.5, and 37.3°C, respectively, for the Desiccant treatment; 34.9, 36.2, and 37.0°C, respectively, for the Paper Towel treatment; Table 3.3). These results suggest that heat loss was relatively greater in magnitude and longer in duration for light birth weight piglets, particularly when not dried. This is due in part to the higher body surface to volume ratio in lighter piglets, and the associated greater heat loss relative to body mass.

These results also suggest that the effects of drying of piglets at birth was relatively more effective at reducing temperature decline in light compared to heavier piglets. This is illustrated by the deviations between Control and other two Drying Treatment temperatures for the birth weight categories for the first 2 h after birth which are presented for the Desiccant and Paper Towel treatments in Figure 3.2a and 3.2b, respectively. There was no difference ($P > 0.05$) in temperature between the Control and either of the Drying Treatments at 10 min after birth (Figure 3.2a, b) suggesting that piglets of all weight categories experienced a similar temperature decline within the first 10 min. The main impact of drying is to reduce evaporation of body surface moisture and associated heat loss and this result suggests that evaporation of amniotic fluid may not be the principle cause of heat loss within the first 10 min after birth.

The deviation in temperature between the Desiccant and Control treatments was greater than 0 ($P \leq 0.05$) for all Birth Weight Categories at all times between 20 and 120 min, with the exception of Heavy piglets at 120 min (Figure 3.2a). In addition, the deviation from the Control was greater ($P \leq 0.05$) for Light than Medium and Heavy piglets at 20, 60, and 120 min. For the Paper Towel treatment, the deviations relative to the Control treatment for the three Birth Weight Categories showed similar trends (Figure 3.2b); however, the deviation between the Light and the two other weight categories was significant at 60 min after birth only. These results suggest that drying piglets was effective at reducing the extent and duration of piglet temperature decline for all birth weights but was relatively more effective in the lighter piglets and that this approach reduces the variation in postnatal temperature decline due to birth weight. There are no other published studies that have evaluated the interaction between Drying Treatments and piglet birth weight with which to compare the results of the current study.

The quadratic regression coefficients for the relationship between piglet birth weight and rectal temperature at each time point for each treatment are presented in Table 3.4. For all Drying Treatments, there was a significant quadratic relationship ($P \leq 0.05$) between piglet birth weight and temperature at all measurement times, except at 1440 min when the relationship was linear (Table 3.4). In addition, at 0 and 1440 min after birth, there were relatively limited differences in the regression coefficients between treatments (Table 3.4). The regression relationships between piglet birth weight and temperature were stronger between 10 and 60 min after birth (R^2 values ≥ 0.58) than subsequently. Le Dividich and Noblet (1981) also reported that birth weight accounted for a significant but decreasing proportion of the variation in the rectal temperature of undried piglets at times between 20 min ($R^2 = 0.76$) and 15 h ($R^2 < 0.05$) after birth. These regression equations (Table 3.4) can be used to predict piglet rectal temperature by management strategy and birth weight to identify which piglets are most at risk of hypothermia and may require additional intervention.

Broken line analyses were carried out for the measurement times that showed a quadratic relationship between birth weight and rectal temperature and these results are presented in Table 3.5. The break point generally decreased with measurement time for the three Drying Treatments from 10 min after birth, although this change was more variable for the Desiccant than the other treatments. In addition, the breakpoint was generally greater for the Control than for the Desiccant or Paper Towel treatments between 20 and 45 min. The break point represents the threshold weight above which variation in piglet temperature is not influenced by birth weight. These results suggest that the proportion of the population of pigs above this threshold increased over time in all treatments and was greater for dried than undried piglets in the first hour after birth. The plateau temperature (i.e., at and above the break point) for the three Drying Treatments decreased to 30 min after birth and, subsequently, generally increased (Table 3.5). In addition, between 30 and 120 min after birth, this temperature was generally lower for the Control than for the other two Drying Treatments. The plateau temperature is that at which piglet temperature is not being influenced by birth weight. These results suggest that, over time, an increasing number of lighter birth weight piglets achieved rectal temperatures equivalent to heavier littermates, and that piglets with lower birth weights that were dried experienced a smaller temperature decline and/or greater temperature recovery across these time periods.

In general, within treatment, the slopes of the regression below the break points increased with measurement time between 10 and 60 min after birth for the Desiccant treatment, and to 120 min for the Control and Paper Towel treatments. The greatest slopes also generally occurred at the same time as the lowest break point weights (with the exception of break points at birth), namely at 60 min for the Desiccant treatment, and 120 min for the Control and Paper Towel treatments. These changes in slopes and break points across measurement times were expected because, as previously described, the temperatures of the Light piglets decreased further and took longer to recover than those of the Medium and Heavy piglets for all treatments. However, compared to the Control and Paper Towel treatments, drying piglets with a desiccant appeared to decrease the time for lighter piglets to recover to a similar temperature as heavier piglets. While there were no significant differences between means for the Desiccant and Paper Towel treatments, these results suggest that the Desiccant treatment may be more effecting at reducing the temperature decline of lower birth weight piglets.

A number of studies estimated the linear regression relationship between piglet body temperature and birth weight at various times after birth, and all showed positive relationships (Pattison et al., 1990; Caldara et al., 2014; Andersen and Pedersen, 2015). However, these studies only evaluated undried piglets, and, therefore, these results can only be compared to the Control treatment of the current study. The magnitude of the regression coefficient reported by other studies varied depending on the measurement time, but were generally greater within the first hour after birth than at subsequent measurement times. For example, Caldara et al. (2014) found that body surface temperature increased by 0.481 and 0.473°C per kg increase in birth weight at 30 and 45 min after birth, respectively. Andersen and Pedersen (2015) found that rectal temperature increased by between 3.1 and 3.9°C/kg at times between 15 and 60 min after birth. Pattison et al. (1990) reported an increase of 1.9°C/kg in rectal temperature at 30 min after birth (the time of the minimum temperature). In the current study, equivalent slopes for the Control below the break point between 20 and 45 min after birth were between 2.22 and 3.10°C/kg, values that are generally within the range found in previous research. However, the slope at 60 min after birth was 7.48°C/kg, which is much greater than previously reported. The current study clearly shows that the regression coefficients for relationships between birth weight and rectal temperature vary markedly depending on both measurement time and interventions.

In conclusion, the results of the current study showed that piglet temperatures decline rapidly in the early postnatal period, especially within the first 30 min after birth. Drying of piglets at birth with either a desiccant or paper towels reduced the extent of this decline after 10 min, which suggests that drying was effective. However, there was significant heat loss immediately after birth that was not affected by drying treatment and most likely not due to evaporative heat loss. Drying, with either a desiccant or paper towels, reduced the temperature decline for piglets of all birth weights, but had relatively greater effects for low birth weight piglets. Birth weight and drying treatment effects on piglet temperature decreased to a minimal level by 24 h after birth, with temperatures for all piglets approaching the levels observed at birth. This suggests that all piglets have the potential to recover from hypothermia and achieve homeothermy. However, the effects of drying on mortality, particularly for low birth weight piglets, warrants further research.

Tables and Figures

Table 3.1. Least-squares means for sow parity, sow rectal temperature, and farrowing pen temperatures during the study, by drying treatment.

	Drying Treatment[1]				
Item.	Control	Desiccant	Paper Towel	SEM	*P*-value
Average sow parity	2.9	4.2	3.6	0.54	0.28
Number of sows by parity[2]					
Parity 2	2	2	3	-	-
Parity 3 and 4	9	7	8	-	-
Parity 5 to 8	6	7	6	-	-
Parity 9+	0	1	1	-	-
Sow rectal temperature, °C					
Start of farrowing	38.5	38.5	38.6	0.15	0.94
After farrowing	38.6	38.7	38.8	0.19	0.72
24 h after farrowing	39.1	39.2	39.3	0.22	0.85
Farrowing pen temperature, °C					
Before Farrowing					
Under heat lamp	33.5	35.4	34.5	0.87	0.32
Side of pen opposite heat lamp	21.2	21.4	21.8	0.47	0.61
Behind sow	21.8	21.9	22.1	0.53	0.93
After Farrowing					
Under heat lamp	34.9	33.8	33.8	0.89	0.61
Side of pen opposite heat lamp	21.3	21.9	22.1	0.52	0.52
Behind sow	21.3	21.9	21.2	0.50	0.53

[1]Control = piglets were not dried; Desiccant = piglets were dried at birth by repeatedly coating and wiping with a desiccant until completely dry; Paper Towel = piglets were dried at birth by wiping with paper towels until completely dry.

[2]Parity = the total number of litters produced by the sow, including the one used in the study.

Table 3.2. Least-squares means for the effect of drying treatment on litter size, birth weight, and rectal temperature of piglets over the first 24 h after birth.

	Drying Treatment[1]				
Item.	Control	Desiccant	Paper Towel	SEM	*P*-value
Number of litters	17	17	18	-	-
Number of piglets born alive					
Total	210	196	212	-	-
Average per litter	12.4	11.5	11.8	0.86	0.79
Piglet birth weight (born alive), kg	1.44	1.41	1.42	0.026	0.64
Piglet rectal temperature, °C					
Time after birth, min					
0	39.1	39.0	38.9	0.04	0.15
10	37.0	36.9	36.8	0.04	0.27
20	35.9[b]	36.7[a]	36.4[a]	0.04	<0.0001
30	35.6[b]	36.9[a]	36.5[a]	0.04	<0.0001
45	36.0[b]	37.3[a]	37.0[a]	0.04	<0.0001
60	36.3[b]	37.7[a]	37.4[a]	0.04	<0.0001
120	37.6[b]	38.3[a]	38.1[a]	0.05	<0.0001
1440	38.8	38.8	38.6	0.05	0.10

[a,b]Within a row, means with differing superscripts differ at $P \leq 0.05$.

[1]Control = piglets were not dried; Desiccant = piglets were dried at birth by repeatedly coating and wiping with a desiccant until completely dry; Paper Towel = piglets were dried at birth by wiping with paper towels until completely dry.

Table 3.3. Least-squares means for the interaction of drying treatment and Birth Weight Category (BWC) on the rectal temperature of piglets over the first 24 h after birth.

		Drying Treatment (DT)[1]				*P*-value
		Control	Desiccant	Paper Towel	SEM	DT x BWC Interaction
Number of piglets born alive		210	196	212	-	-
BW Category[2]						
Light		18	31	25	-	-
Medium		105	92	89	-	-
Heavy		87	73	98	-	-
Piglet rectal temperature, °C						
Time after birth, min						
0	BWC[2]				0.05	0.21
	Light	38.9	38.9	38.7	-	-
	Medium	39.1	39.0	38.8	-	-
	Heavy	39.2	39.0	39.0	-	-
10	BWC[2]				0.05	<0.0001
	Light	35.9^{b}	35.9^{b}	36.0^{b}	-	-
	Medium	36.8^{a}	36.9^{a}	36.6^{a}	-	-
	Heavy	37.5^{a}	37.4^{a}	37.3^{a}	-	-
20	BWC[2]				0.05	<0.0001
	Light	34.0^{d}	35.5^{c}	35.1^{c}	-	-
	Medium	35.7^{c}	36.5^{b}	36.2^{b}	-	-
	Heavy	36.5^{b}	37.3^{a}	37.0^{a}	-	-
30	BWC[2]				0.05	<0.0001
	Light	33.6^{f}	35.5^{e}	34.9^{e}	-	-
	Medium	35.4^{e}	36.9^{bc}	36.3^{d}	-	-
	Heavy	36.3^{cd}	37.6^{a}	37.2^{ab}	-	-
45	BWC[2]				0.05	<0.0001
	Light	33.5^{f}	35.9^{e}	35.2^{e}	-	-
	Medium	35.7^{e}	37.3^{bc}	36.6^{d}	-	-
	Heavy	36.7^{cd}	38.0^{a}	37.8^{ab}	-	-
60	BWC[2]				0.05	<0.0001
	Light	33.4^{d}	36.3^{c}	35.5^{c}	-	-
	Medium	36.1^{c}	37.8^{ab}	37.1^{b}	-	-
	Heavy	37.1^{b}	38.3^{a}	38.2^{a}	-	-
120	BWC[2]				0.05	<0.0001
	Light	35.2^{e}	37.5^{cd}	36.7^{d}	-	-
	Medium	37.6^{c}	38.3^{ab}	38.0^{bc}	-	-
	Heavy	38.2^{ab}	38.7^{a}	38.6^{a}	-	-
1440	BWC[2]				0.05	0.001
	Light	38.0^{d}	38.5^{abcd}	38.3^{cd}	-	-
	Medium	38.8^{ab}	38.9^{ab}	38.5^{bcd}	-	-
	Heavy	38.9^{a}	38.8^{ab}	38.7^{abc}	-	-

[a,b,c,d,e,f]For each measurement time, means within the DT x BWC interaction with differing superscripts differ at $P \leq 0.05$.

[1]Control = piglets were not dried; Desiccant = piglets were dried at birth by repeatedly coating and wiping with a desiccant until completely dry; Paper Towel = piglets were dried at birth by wiping with paper towels until completely dry.

[2]Light = < 1.0 kg; Medium = 1.0 to 1.5 kg; Heavy = > 1.5 kg.

Table 3.4. Regression coefficients for the quadratic relationships between piglet birth weight (BW) and rectal temperatures over the first 24 h after birth (as deviations to the Control for the Desiccant and Paper Towel treatments).

Item.		Coefficient[2]			SE			*P*-value			
Time after birth, min	Treatment[1]	Intercept	BW	BW[2]	Intercept	BW	BW[2]	Intercept	BW	BW[2]	R^2
0	Control	39.17	0.27	-0.47	0.085	0.080	0.151	<0.0001	0.001	0.002	
	Desiccant	-0.17	-0.11	0.38	0.121	0.120	0.200	0.17	0.34	0.06	0.50
	Paper Towel	-0.28	0.05	0.56	0.120	0.116	0.217	0.02	0.69	0.01	
10	Control	37.02	1.44	-0.49	0.119	0.137	0.258	<0.0001	<0.0001	0.06	
	Desiccant	0.06	0.24	-0.61	0.169	0.205	0.342	0.73	0.24	0.08	0.58
	Paper Towel	-0.09	-0.37	-0.30	0.167	0.199	0.373	0.59	0.06	0.42	
20	Control	35.95	2.13	-1.15	0.137	0.163	0.307	<0.0001	<0.0001	0.0002	
	Desiccant	0.84	-0.24	0.05	0.195	0.243	0.406	<0.0001	0.33	0.91	0.64
	Paper Towel	0.68	-0.74	-0.56	0.192	0.237	0.443	0.001	0.002	0.21	
30	Control	35.76	2.40	-1.54	0.160	0.201	0.377	<0.0001	<0.0001	<0.0001	
	Desiccant	1.35	-0.09	-0.06	0.228	0.300	0.501	<0.0001	0.76	0.9	0.64
	Paper Towel	0.97	-0.73	-0.21	0.225	0.291	0.546	<0.0001	0.01	0.7	
45	Control	36.11	2.69	-1.70	0.182	0.228	0.427	<0.0001	<0.0001	<0.0001	
	Desiccant	1.52	-0.32	-0.56	0.260	0.340	0.568	<0.0001	0.35	0.32	0.64
	Paper Towel	1.13	-0.70	-0.39	0.257	0.330	0.618	<0.0001	0.03	0.53	
60	Control	36.63	3.07	-2.82	0.187	0.247	0.463	<0.0001	<0.0001	<0.0001	
	Desiccant	1.43	-0.75	0.40	0.268	0.368	0.616	<0.0001	0.04	0.52	0.62
	Paper Towel	1.10	-1.05	0.50	0.265	0.360	0.675	0.0001	0.004	0.45	
120	Control	37.95	2.29	-2.69	0.149	0.233	0.427	<0.0001	<0.0001	<0.0001	
	Desiccant	0.60	-0.91	1.12	0.214	0.342	0.570	0.01	0.01	0.05	0.48
	Paper Towel	0.52	-0.84	-0.32	0.212	0.337	0.628	0.02	0.01	0.61	
1440	Control	38.82	0.63	-0.35	0.124	0.140	0.264	<0.0001	<0.0001	0.19	
	Desiccant	0.00	-0.34	-0.27	0.176	0.211	0.349	0.99	0.11	0.44	0.36
	Paper Towel	-0.22	-0.34	-0.29	0.174	0.203	0.382	0.21	0.04	0.45	

[1]Control = piglets were not dried; Desiccant = piglets were dried at birth by repeatedly coating and wiping with a desiccant until completely dry; Paper Towel = piglets were dried at birth by wiping with paper towels until completely dry.

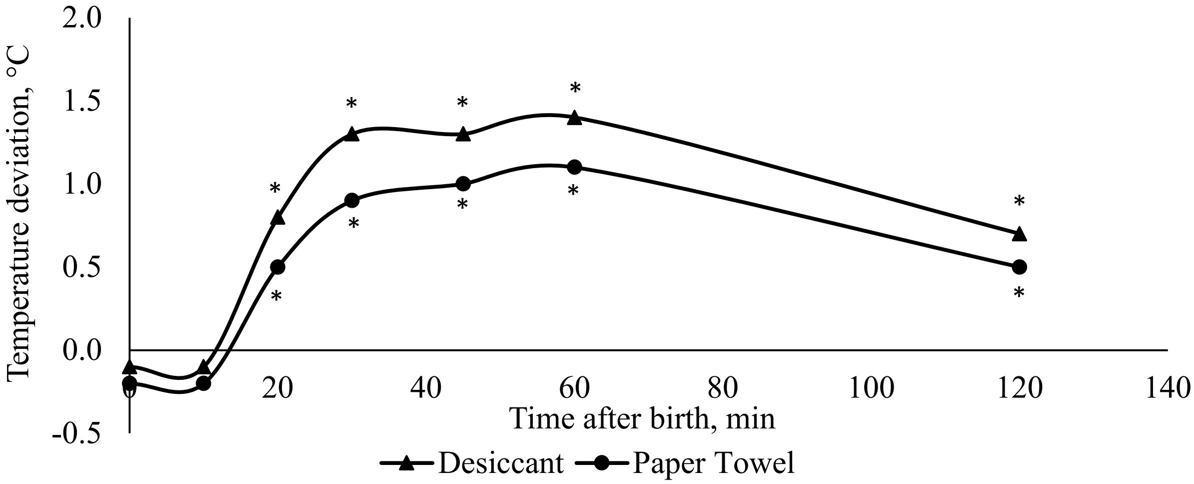
[2]BW = Birth weight, kg. Using centered birth weight and squared birth weight, with a mean of 1.42 kg. Desiccant and Paper Towel coefficients as a deviation from the Control.

Table 3.5. Broken line regression for the effect of piglet birth weight on rectal temperature over the first 24 h after birth.

Time after birth, min	Treatment[1]	Linear regression below break point		Break point, kg	Average temperature above the break point, °C
		Intercept, °C	Slope of birth weight, °C/kg		
0	Control	36.03	3.73	0.83	39.13
	Desiccant	35.85	4.50	0.70	39.00
	Paper Towel	38.39	0.35	2.07	39.12
10	Control	34.79	1.55	2.12	38.08
	Desiccant	34.17	2.08	1.62	37.54
	Paper Towel	34.84	1.40	2.18	37.89
20	Control	32.70	2.22	2.06	37.28
	Desiccant	33.77	2.09	1.86	37.66
	Paper Towel	32.67	2.84	1.52	36.98
30	Control	31.84	2.67	1.90	36.93
	Desiccant	32.20	3.68	1.46	37.57
	Paper Towel	32.37	3.06	1.60	37.27
45	Control	31.58	3.10	1.83	37.24
	Desiccant	31.91	4.35	1.38	37.90
	Paper Towel	32.02	3.70	1.58	37.86
60	Control	27.22	7.48	1.29	36.87
	Desiccant	27.38	10.19	1.04	38.02
	Paper Towel	32.05	4.06	1.53	38.25
120	Control	27.89	8.71	1.16	37.96
	Desiccant	35.33	2.35	1.43	38.69
	Paper Towel	32.39	4.70	1.32	38.57

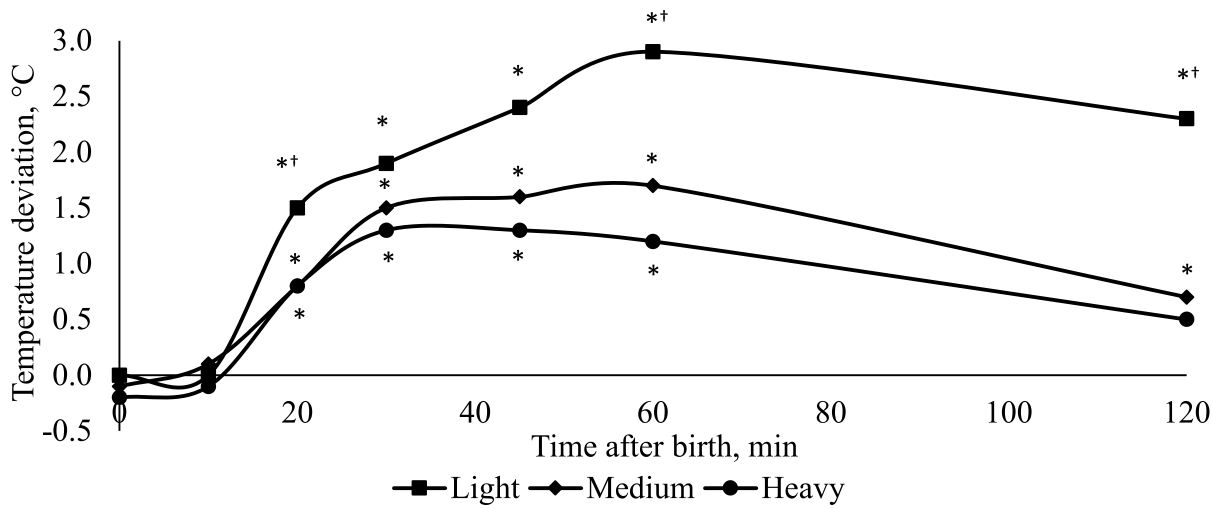
[1]Control = piglets were not dried; Desiccant = piglets were dried at birth by repeatedly coating and wiping with a desiccant until completely dry; Paper Towel = piglets were dried at birth by wiping with paper towels until completely dry.

Figure 3.1. Deviation in piglet rectal temperature between dried (Desiccant or Paper Towel) and undried (Control) treatments over the first 2 h after birth.



*Deviation to the Control treatment different from 0, at $P \leq 0.05$.

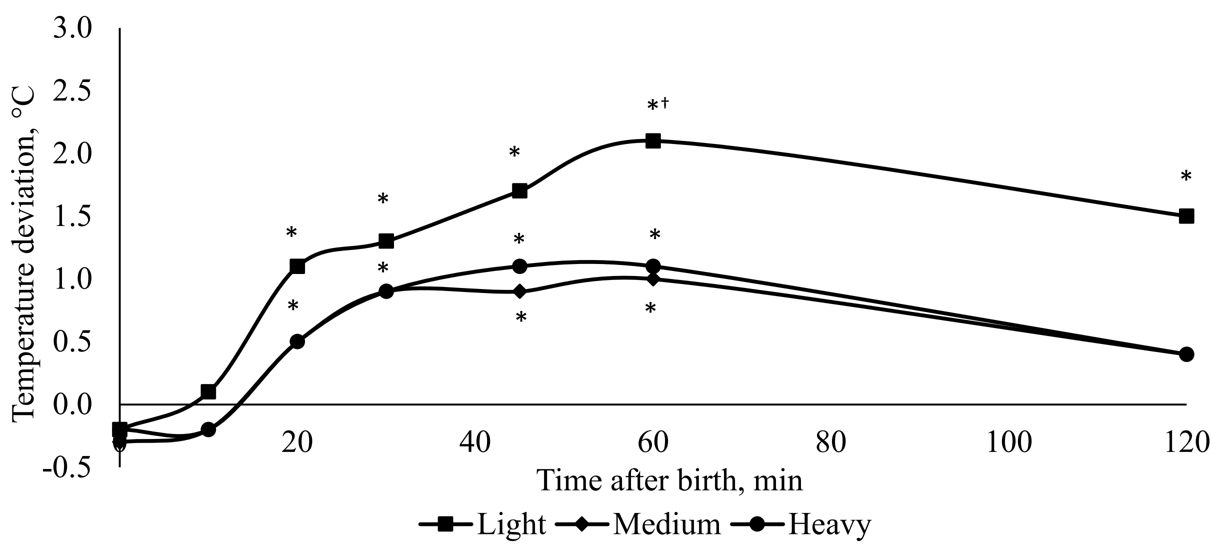
Figure 3.2a. Deviation in piglet rectal temperature between the Desiccant and Control treatments over the first 2 h after birth, for Light (< 1.0 kg), Medium (1.0 to 1.5 kg), and Heavy (> 1.5 kg) birth weight categories.



†Difference in the magnitude between treatment deviations of Light and Medium birth weight categories, at $P \leq 0.05$. There were no differences ($P > 0.05$) between deviations for Medium and Heavy birth weight categories.

*Deviation to the Control treatment different to 0, within Birth Weight Category, at $P \leq 0.05$.

Figure 3.2b. Deviation in piglet rectal temperature between the Paper Towel and Control treatments over the first 2 h after birth, for Light (< 1.0 kg), Medium (1.0 to 1.5 kg), and Heavy (> 1.5 kg) birth weight categories.



†Difference in the magnitude between treatment deviations of Light and Medium birth weight categories, at $P \leq 0.05$. There were no differences ($P > 0.05$) between deviations for Medium and Heavy birth weight categories.

*Deviation to the Control treatment different to 0, within Birth Weight Category, at $P \leq 0.05$.

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CHAPTER 4: Effect of drying and/or warming piglets at birth on rectal temperature over the first 24 h after birth

Abstract

Piglets experience a rapid decrease in body temperature immediately after birth, increasing the risk of mortality. The objective of this study was to determine the effect of drying and/or warming piglets at birth on rectal temperature over the first 24 h after birth. The study was carried out at a commercial sow facility using a completely randomized design with four treatments (applied to piglets at birth): Control (no drying or warming), Desiccant (dried using a desiccant), Warming Box (placed in a box under a heat lamp for 30 min), and Desiccant+Warming Box (both dried and warmed as above). Farrowing pens had one heat lamp, temperatures under which were similar to the warming box (35°C). A total of 68 litters (866 piglets) were randomly allotted to a treatment at the birth of the first piglet. At birth, each piglet was identified with a numbered ear tag and weighed; rectal temperature was measured at 0, 10, 20, 30, 45, 60, 120, and 1440 min after birth. Data were analyzed using a repeated measures model using PROC MIXED of SAS. Litter was the experimental unit, piglet was a subsample of the litter; the model included the fixed effects of treatment, time (the repeated measure), and the interaction. Rectal temperatures at birth and 1440 min after birth were similar ($P > 0.05$) for all treatments. At all times between 10 and 120 min after birth, Control piglets had lower ($P \leq 0.05$) temperatures than the other three treatments. The Desiccant and Warming Box treatments had similar ($P > 0.05$) temperatures at most measurement times, but the Desiccant+Warming Box treatment had the highest ($P \leq 0.05$) rectal temperatures at most times between 10 and 60 min. In addition, for all treatments, Light (< 1.0 kg) birth weight piglets had lower ($P \leq 0.05$) temperatures than Medium (1.0 to 1.5 kg) or Heavy (> 1.5 kg) piglets at all times between 10 and

120 min. In addition, at these measurement times, the deviation in temperature between the Control and the other three treatments was greater for Light than Medium or Heavy piglets. In conclusion, both drying and warming piglets at birth significantly increased rectal temperatures between 10 and 120 min after birth, with the combination of the two interventions having the greatest effect, especially for low birth weight piglets.

Introduction

Newborn piglets have little body surface insulation and limited capacity for thermoregulatory heat production, resulting in a high critical temperature (around 35°C; Mount, 1959). Due to the lower thermoneutral zone for sows (Black et al., 1993), farrowing rooms are typically kept at temperatures considerably below the piglets' critical temperature. The resulting temperature gradient leads to considerable heat loss from the body surface of the piglet, mainly due to convection and radiation. In addition, piglets are born wet and experience heat loss due to evaporation of the amniotic fluids. Therefore, in the absence of any intervention, all piglets will experience some degree of hypothermia under typical farrowing room conditions. This results in decreased mobility and vigor, a diminished ability to compete with littermates during suckling, and, therefore, reduced colostrum intake (Le Dividich and Noblet; 1981). This reduced energy intake and decreased immune status predisposes piglets to mortality from secondary causes such as starvation, disease, and crushing (Devillers et al., 2011). Low birth weight piglets are at the greatest risk of hypothermia immediately after birth, due to a higher body surface:volume ratio, and, therefore, relatively greater potential to lose more heat than heavier littermates (Herpin et al., 2002).

One method to limit this heat loss is to reduce the temperature gradient by increasing the environmental temperature that piglets experience after birth. However, increasing the temperature of the farrowing room, although potentially beneficial for the piglets, would lead to heat stress for the sows, resulting in reduced feed intake and milk production (Farmer and Quesnel, 2009). To address this issue, most farrowing pens include a localized area at a higher temperature using, for example, heat lamps. However, newborn piglets are generally not confined to the heated area and are more attracted to the sow (Houbak et al., 2006; Pedersen et al., 2006). Warming boxes (a box placed under the heat source) can be utilized to confine piglets to the heated area for short periods of time after birth to minimize heat loss. Another method of reducing this early postnatal heat loss is through limiting the evaporation of the amniotic fluid from the body surface by drying piglets at birth (removing the source of evaporation). In this regard, Vande Pol et al. (2020) showed that drying piglets with a desiccant was effective at reducing piglet temperature loss in the early postnatal period. In theory, the combination of drying and warming piglets should have a greater effect on reducing postnatal heat loss in the newborn piglet than either approach applied separately because it reduces heat loss via three different routes (evaporation, convection, and radiation).

Although both drying and warming of piglets at or near birth are widely used in commercial practice, there has been little published research on the effects of these approaches. Therefore, the objective of this study was to determine the effects of drying and/or warming piglets at birth on rectal temperatures over the first 24 h after birth.

Materials and Methods

This study was conducted in the farrowing facilities of a commercial breed-to-wean farm of The Maschhoffs, LLC, located near Crawfordsville, IN during the months of January through March 2018. The experimental protocol was approved by the University of Illinois Institutional Animal Care and Use Committee prior to the initiation of the research.

Animals, Experimental Design, Treatments, and Allotment

A total of 68 litters (866 piglets) were used in the study. Sows were from commercial dam lines of Yorkshire and Landrace origin that had been mated to commercial sire lines. The study used a completely randomized design, with litter as the experimental unit (17 litters per treatment) and piglet as a subsample of the litter, to compare four treatments (applied at birth): Control (no drying or warming); Desiccant (piglets were completely dried by repeatedly coating with a commercial cellulose-based desiccant); Warming Box [piglets were placed in a plastic box under a heat lamp (temperature in the box 35.3 ± 3.64°C) for 30 min]; Desiccant+Warming Box [piglets dried and warmed as above (temperature in the box 35.9 ± 2.94°C)]. Litters were randomly allotted to treatment at the start of farrowing after the birth of the first piglet, with the restriction that dam genotype and parity were balanced across treatments.

Housing and Management

Sows were housed in individual farrowing crates, each located within a farrowing pen which had either woven metal or perforated plastic flooring. Crate dimensions were 0.55 m by 1.95 m, giving a floor space within the crate of 1.07 m^2; pen dimensions were 1.52 m by 2.07 m, giving a total pen floor space of 3.15 m^2. Crates were equipped with a sow-operated feed dispenser attached to a feed trough, and a nipple-type water drinker for the sow. An infrared heat lamp was suspended over an insulated rubber mat located in the center of the floor area on one side of the farrowing pen (average temperature under the heat lamp was 36.1 ± 3.15°C). For the treatments that used a warming box, the lamp was suspended over the plastic box throughout farrowing, with piglets being placed in the warming box after birth and removed after 30 min and returned to the farrowing pen, at the udder. Thermostats to maintain farrowing room temperature were set to 22.5°C throughout the study period, and temperatures were regulated using fans and heaters.

Management in the farrowing facility was according to unit protocols, which were generally in line with standard commercial practices. Sows that had not farrowed by 116 d of gestation were induced to farrow on the following day using Lutalyse (1 injection of 1 mL given at 0600 h; Zoetis; Parsippany, NJ); the identity of each sow induced and date of induction were recorded. The farrowing process was monitored continuously by the investigators; if the interval between the births of piglets exceeded 60 min, the investigator checked the birth canal for obstructions, and assisted the farrowing process as needed.

Procedures and Measurements

Piglet and sow rectal temperatures were measured using a HSTC-TT-K-24S-36 thermocouple attached via a SMPW-K-M connector to a dual input K/J digital thermometer (HH801A; Omega; Stamford, CT). A different thermocouple was used for the piglets and the sows. Thermometers were calibrated each week during the study period by taking measurements in a temperature-controlled chamber that was set at temperatures that encompassed the expected range (i.e., 30, 32, 34, 36, 38, and 40°C). Measured and set temperatures were used to develop regression equations for both sow and piglet thermocouples, and all rectal temperature measurements taken during the study were adjusted using these regression equations.

Sow rectal temperature was measured (at a depth of 10 cm) at the start and end of the farrowing process and at 24 h after farrowing. Piglet rectal temperature was measured at birth, piglets were given a uniquely numbered ear tag for identification, and treatments were applied. Piglet temperatures were also measured at 10, 20, 30, 45, 60, 120, and 1440 min after birth. After treatments were completed (immediately for the Control and Desiccant treatments and after

30 min for the Warming Box and Desiccant+Warming Box treatments), piglets were returned to the farrowing pen, being placed at the udder. Piglets were weighed on the day of birth using a Brecknell LPS-15 bench scale (Avery Weigh-Tronix; Fairmont, MN). Scales were calibrated daily prior to use with a standard test weight.

Ambient temperatures in each farrowing pen [behind and at either side of the sow (one of these measurements being under the heat lamp)] were measured at the beginning and end of the farrowing process using a digital infrared thermometer [TOOGOO GM320 LCD digital infrared thermometer gun (Shenzhen IMC Digital Technology Co.; Shenzhen, China)].

Statistical Analysis

The litter of piglets was the experimental unit for all measurements; piglet was a sub-sample of litter. The PROC UNIVARIATE procedure of SAS (SAS Inst. Inc., Cary, NC) was used to verify normality and homogeneity of variances of the residuals. All variables conformed to the assumptions of normality and homogeneity and were analyzed using the PROC MIXED procedure of SAS (Littell et al., 1996). The study was carried out using a completely randomized design; the model used for the analysis of sow parameters and litter measurements accounted for the fixed effect of treatment. The model used for analysis of treatment differences in piglet birth weight also included the random effect of piglet within litter.

Treatment effects on piglet rectal temperatures were analyzed using a repeated measures analysis, with the model accounting for the fixed effects of treatment, measurement time, and the interaction, and the random effect of piglet within litter. A repeated-measures statement was included in the model with measurement time as the REPEATED term and piglet as the SUBJECT term.

An analysis was carried out to determine if the response to treatments differed according to piglet birth weight. The data set was divided into three Birth Weight Categories: Light (< 1.0 kg), Medium (1.0 to 1.5 kg), or Heavy (> 1.5 kg). The maximum weight for the Light category (i.e., 1.0 kg) represented the birth weight below which pre-weaning mortality increases substantially (Zotti et al., 2017). The minimum weight for the Heavy category (i.e., 1.5 kg) represented the weight above which pre-weaning mortality is relatively unaffected by birth weight (Zotti et al., 2017). Piglet rectal temperature data at each measurement time were analyzed using a statistical model that included the fixed effects of Birth Weight Category, treatment, and the interaction, and the random effect of piglet within litter.

For all analyses, differences between least-squares means were separated using the PDIFF option of SAS, and differences were considered significant at $P \leq 0.05$. All P-values were adjusted using a Tukey's adjustment for multiple comparisons.

Results and Discussion

Sow parameters and farrowing pen temperatures have been summarized by treatment in Table 4.1. There were no differences ($P > 0.05$) between treatments for any of the parameters or measurements. In general, the sows used in the study and the temperature conditions in the farrowing facilities were typical of U.S. commercial production. The majority of sows on the study were between parities 2 and 8. Average sow temperatures before and after farrowing were between 38.2 and 38.7°C, which is typical for farrowing sows (Littledike et al., 1979). Average farrowing room temperatures (between 21.4 and 22.6°C; Table 4.1) were close to the set point (22.5°C).

Effect of Treatments on the Temperature Decline of Piglets

Least-squares means for the drying and/or warming treatments for litter size, piglet birth weight, and piglet rectal temperature over the first 24 h after birth are presented in Table 4.2. Number of piglets born alive (12.3 to 13.3/litter) were similar ($P > 0.05$) across treatments and were comparable to values for U.S. herds reported by PigChamp at the time that this study was conducted (13.2 piglets/litter; 2017, 2018). There were no differences between treatments ($P > 0.05$) for piglet birth weights (Table 4.2), which were similar to those reported in recent studies (e.g., Feldspausch et al., 2019).

There was no effect ($P > 0.05$) of treatment on rectal temperatures at birth (Table 4.2) with the means for all treatments being the same (Table 4.2). This was as expected, as birth temperatures were taken before the treatments were applied. Birth temperatures observed in previous research have varied, from 37.0°C (Kammersgaard et al., 2011) to 40.5°C (Pomeroy, 1953). In addition, Kammersgaard et al. (2011) found considerable variation within the same study (between 37.0 and 41.5°C). Piglet temperatures decline rapidly after birth (Table 4.2), and variation between studies for birth temperature may reflect differing times of measurement relative to the time of birth.

The decline in rectal temperature of Control piglets after birth, which provides an estimate of changes experienced by undried piglets, was extensive, with the minimum temperature, which was at 30 min, being 3.7°C lower than at birth (Table 4.2). Subsequently, temperatures increased and approached the level observed at birth by 1440 min. A number of studies have also found that the minimum temperature of untreated piglets occurred at 30 min after birth; however, values at this time varied between studies ranging from 33.6°C (Xiong et al., 2018) to 36.6°C (Pattison et al., 1990). Most studies have found that, on average, temperatures reach levels close to those at birth by 24 h after birth (McGinnis et al., 1981; Xiong et al., 2018; Cooper et al., 2019).

Piglets on the Desiccant and Warming Box treatments had higher ($P \leq 0.05$) temperatures than those on the Control treatment at all times between 10 and 120 min after birth (Table 4.2). In addition, temperatures were similar for the Desiccant and Warming Box treatments at 10, 20, 30, and 120 min after birth, but were lower ($P \leq 0.05$) for the Warming Box treatment at 45 and 60 min. However, the differences at these two times were relatively small (0.4°C). Minimum temperatures of piglets on both of these treatments occurred earlier and were higher ($P \leq 0.05$) than those on the Control (Table 4.2). Both drying and warming of piglets at birth have been used in commercial production, however, there has been limited research comparing these approaches. Most studies have shown that drying reduced the extent of piglet temperature decline in the first 60 min after birth; however, the magnitude of the effect varied between studies. This may in part be due to the use of different drying materials and/or the timing of measurement of rectal temperature after birth (e.g., Berbigier et al., 1978; McGinnis et al., 1981). However, studies have also shown variation in the effectiveness of using a desiccant as the drying agent for reducing postnatal temperature decline. Cooper et al. (2019) found that the maximum difference in temperature between undried piglets and those dried with a desiccant was at 45 min and was 2.4°C, whereas for Vande Pol et al. (2020), this was at 60 min and was 1.4°C. In the current study, the maximum difference was 2.2°C and was at 45 min after birth (Table 4.2). Further research is required to establish the reasons for this variation in response to similar drying treatments.

Published studies related to the warming of piglets at birth are limited in number and varied considerably in approach. Pedersen et al. (2016) found that confining piglets under a radiant heat source (at 34°C) for 2 h compared to leaving them at room temperature (at 20.9°C) increased the minimum temperature by between 1.2 to 1.4°C, which is similar to the results for the Warming treatment in the current study. In contrast, Pattison et al. (1990) showed a small increase in temperature (0.3°C at 60 min after birth) from confining piglets in a heated creep area for 45 min. However, the warming treatment in that study started at 15 min after birth, by which time piglet temperatures would have decreased considerably. A number of studies added localized heat sources to the farrowing pen, without confining piglets to the heated areas (e.g., McGinnis et al., 1981; Andersen and Pedersen, 2015) and found a smaller effect on rectal temperatures than the current study, suggesting that confining piglets to a heated area was a more effective approach. Instead of providing a localized heat source for warming piglets, some studies have evaluated the impact of increasing the temperature of either the farrowing pen or the entire room. Le Dividich and Noblet (1981) found that the rectal temperature of piglets kept at an ambient temperature of 30 to 32°C was 1.6°C higher (at 20 min after birth) than that of piglets kept at 18 to 20°C. Pedersen et al. (2013) found that piglets in rooms at 25°C had higher temperatures at 30 min after birth (0.9°C) than those in rooms kept at 15 or 20°C. In comparison, the current study found a difference between the Warming Box and Control treatments of 2.0°C at this time.

In the current study, both drying and warming were effective at reducing piglet temperature decline early postnatal period; however, the combination of these two approaches was most effective. The Desiccant+Warming Box treatment resulted in the highest ($P \leq 0.05$) temperatures compared to all other treatments between 20 and 45 min after birth, and the highest minimum temperature at the earliest time after birth (Table 4.2). This is the first study that we are aware of that combined these treatments. As previously discussed, drying of piglets should minimize evaporative heat loss, whereas warming piglets reduces convective and radiative heat loss by reducing the temperature gradient between the piglet and the environment. Given that these two interventions, applied separately, had a relatively similar effect on postnatal body temperature changes suggests that the magnitude of heat loss by these routes are relatively similar. However, the combination of drying and warming should reduce heat loss by both routes, and the results of this study indicate that this was the most effective method of reducing piglet temperature decline within the first hour after birth. While all of the previous research, including the current study, showed that drying and/or warming piglets increased rectal temperatures within the first hour after birth, most found that the magnitude of this effect subsequently decreased and was minimal by 24 h after birth, when temperatures of piglets on all treatments approached the levels observed at birth.

Effect of Piglet Birth Weight on Responses to Treatments

Least-squares means for the treatment by Birth Weight Category interaction are presented in Table 4.3. There were interactions ($P \leq 0.05$) at all measurement times except at birth. At all other measurement times and for all treatments, Light piglets had lower ($P \leq 0.05$) temperatures than the other Birth Weight Categories. Medium piglets had lower temperatures than Heavy ($P \leq 0.05$) at all times between 10 and 60 min for the Control, Desiccant, and Warming Box treatments, and at 10 min for the Desiccant+Warming Box treatment (Table 4.3). At all other times, there were no differences ($P > 0.05$) between temperatures of Medium and Heavy piglets for any of the four treatments. Previous research has also shown that the extent and duration of the temperature decline after birth is greater in low birth weight piglets than in heavier littermates (Pattison et al., 1990; Pedersen et al., 2016; Cooper et al., 2019; Vande Pol et al., 2020). Lighter piglets are predisposed to chilling (Muns et al., 2016), having a high body surface area to volume ratio, low body fat for insulation (Curtis, 1974), and limited energy reserves (glycogen and fat) for heat production (Lossec et al., 1998).

Piglets of all Birth Weight Categories on the three drying and/or warming treatments had higher ($P \leq 0.05$) temperatures than those on the Control between 10 and 120 min after birth, with the exception of Light piglets on the Desiccant treatment, which had a similar ($P > 0.05$) temperature to the Control at 10 min after birth (Table 4.3). Therefore, the treatment by Birth Weight Category interactions were largely due to differences in the magnitude of the temperature deviation between treatments within each Birth Weight Category. This is illustrated by the deviations between the temperatures of the Control and the other three treatments for each Birth Weight Category at each measurement time, which are presented in Figure 4.1a, b, c. For all three treatments, the deviations from the Control treatment were similar ($P > 0.05$) for Medium and Heavy piglets at all measurement times from 10 to 120 min, but were much greater ($P \leq 0.05$) for Light piglets between 20 and 120 min after birth. For example, at 30 min after birth, Light piglets on the Desiccant+Warming Box treatment had temperatures that were 4.3°C higher than those on the Control treatment. In comparison, this difference was 3.0°C for Medium and 2.6°C for Heavy piglets at this time (Figure 4.1c). For all Birth Weight Categories, the minimum temperature of dried and/or warmed piglets occurred earlier and was greater than the Control. For example, the minimum temperature of Light piglets occurred at 10 min after birth for the Desiccant+Warming Box treatment compared to 45 min for the Control (Table 4.3). These results suggest that drying and warming, either singularly or in combination, reduced the extent and duration of temperature decline for piglets of all birth weights, but had a greater effect for those of low birth weight.

Two studies have evaluated the potential interaction between piglet birth weight and intervention treatments for postnatal temperature changes, and both found similar results to the current experiment. Pedersen et al. (2016) found that adding a radiant heat source to the farrowing pen increased piglet rectal temperatures between 0 and 120 min after birth and reduced the time piglets had temperatures below 35°C for all weight groups, with these effects being greater for light than heavy piglets. Similarly, Vande Pol et al. (2020) found that drying piglets at birth reduced the magnitude and duration of temperature decline to a greater extent in lower compared to heavier birth weight piglets.

In conclusion, the results of the current study confirm that birth weight is an important factor influencing piglet temperatures in the early postnatal period, with lower birth weight piglets experiencing the greatest extent and duration of temperature decline. Drying or warming piglets at birth were similarly effective at reducing these temperature changes, with the combination being most effective, especially for low birth weight piglets.

Tables and Figures

Table 4.1. Summary of sow parity and rectal temperature and farrowing pen temperatures during the study by treatment.

	Treatment[1]					
Item.	Control	Desiccant	Warming Box	Desiccant+ Warming Box	SEM	*P*-value
Average sow parity	3.8	3.5	4.1	4.4	0.71	0.84
Number of sows by parity[2]						
Parity 1	0	0	0	0	-	-
Parity 2	4	5	4	1	-	-
Parity 3 and 4	7	5	4	9	-	-
Parity 5 to 8	4	6	7	5	-	-
Parity 9+	2	1	2	2	-	-
Sow rectal temperature, °C						
Start of farrowing	38.2	38.2	38.2	38.3	0.13	0.89
After farrowing	38.4	38.4	38.4	38.4	0.15	0.95
24 h after farrowing	38.4	38.7	38.6	38.6	0.18	0.81
Farrowing pen temperature, °C						
Before Farrowing						
Under heat lamp	35.9	35.9	36.2	35.1	0.79	0.79
Side of pen opposite heat lamp	22.6	22.2	21.5	22.0	0.59	0.62
Behind sow	22.3	22.1	21.7	21.4	0.49	0.57
After Farrowing						
Under heat lamp	35.8	35.0	36.1	34.6	0.67	0.33
Side of pen opposite heat lamp	22.7	22.3	22.2	22.4	0.49	0.90
Behind sow	21.8	21.8	21.6	21.6	0.46	0.97

[1]Control = piglets were not dried; Desiccant = piglets were dried at birth by coating with a desiccant; Warming Box = piglets were placed in a warming box for 30 min after birth; Desiccant+Warming Box = piglets were dried at birth by coating with a desiccant, then placed in a warming box for 30 min.

[2]Parity = total number of litters including the one used in the study.

Table 4.2. Least-squares means for the effect of treatment on litter size, birth weight, and rectal temperature of piglets over the first 24 h after birth.

	Treatment[1]					
	Control	Desiccant	Warming Box	Desiccant+ Warming Box	SEM	*P*-value
Number of litters	17	17	17	17	-	-
Number of piglets born alive						
Total	226	209	214	217	-	-
Average per litter	13.3	12.3	12.6	12.8	0.85	0.86
Piglet birth weight (born alive), kg	1.46	1.46	1.45	1.44	0.023	0.89
Piglet rectal temperature, °C						
Time after birth, min						
0	38.9	38.9	38.9	38.9	0.03	0.98
10	36.7[c]	37.1[b]	37.4[ab]	37.6[a]	0.03	<0.0001
20	35.6[c]	36.9[b]	37.0[b]	37.8[a]	0.03	<0.0001
30	35.2[c]	37.2[b]	37.2[b]	38.1[a]	0.03	<0.0001
45	35.5[d]	37.7[b]	37.3[c]	38.2[a]	0.03	<0.0001
60	36.1[c]	38.1[a]	37.7[b]	38.4[a]	0.03	<0.0001
120	37.7[b]	38.5[a]	38.3[a]	38.6[a]	0.03	<0.0001
1440	38.7	38.7	38.6	38.7	0.03	0.14

[a,b,c,d]Within a row, means with differing superscripts differ at $P \leq 0.05$.

[1]Control = piglets were not dried; Desiccant = piglets were dried at birth by coating with a desiccant; Warming Box = piglets were placed in a warming box for 30 min after birth; Desiccant+Warming Box = piglets were dried at birth by coating with a desiccant then placed in a warming box for 30 min.

Table 4.3. Least-squares means for the interaction of Treatment (T) and Birth Weight Category (BWC) on the rectal temperature of piglets over the first 24 h after birth.

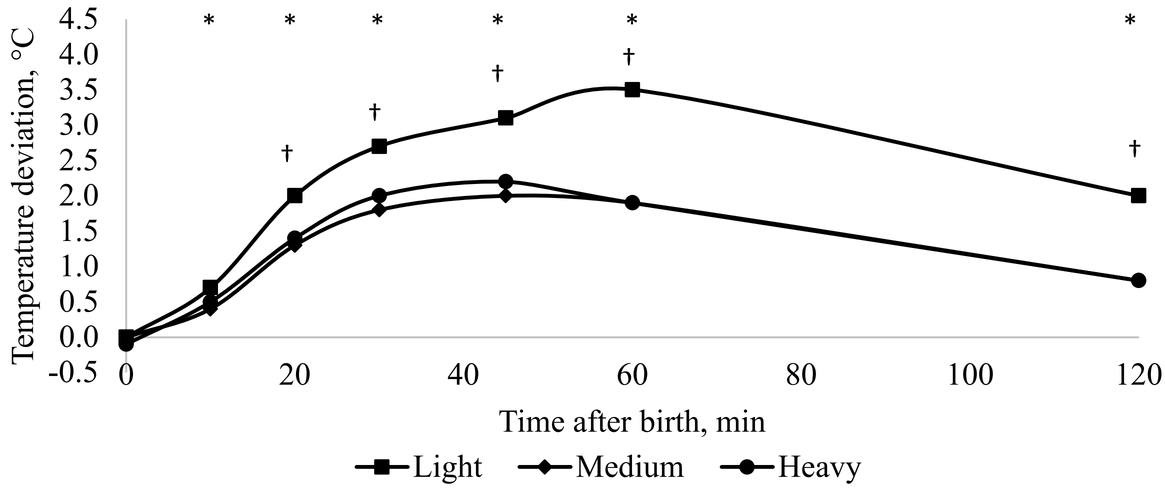
	Treatment (T)[1]					*P*-value
Item.	Control	Desiccant	Warming Box	Desiccant+ Warming Box	SEM	BWC x T Interaction
Number of piglets born alive						
Light	15	20	18	33	-	-
Medium	101	91	104	77	-	-
Heavy	110	98	92	107	-	-
Piglet rectal temperature, °C						
Time after birth, min						
0 BWC[2]					0.04	0.09
Light	38.7	38.7	38.6	38.7	-	-
Medium	38.8	38.8	38.8	38.8	-	-
Heavy	39.0	38.9	39.1	38.9	-	-
10 BWC[2]					0.04	<0.0001
Light	35.5^{e}	36.2^{de}	36.4^{d}	36.9^{cd}	-	-
Medium	36.6^{d}	37.0^{c}	37.1^{c}	37.5^{b}	-	-
Heavy	37.0^{c}	37.5^{b}	37.8^{ab}	37.8^{a}	-	-
20 BWC[2]					0.04	<0.0001
Light	33.8^{g}	35.8^{ef}	36.0^{ef}	37.1^{cd}	-	-
Medium	35.4^{f}	36.7^{d}	36.9^{d}	37.7^{ab}	-	-
Heavy	36.0^{e}	37.4^{bc}	37.5^{bc}	38.1^{a}	-	-
30 BWC[2]					0.04	<0.0001
Light	33.1^{g}	35.8^{e}	36.1^{e}	37.4^{cd}	-	-
Medium	35.1^{f}	36.9^{d}	37.1^{d}	38.1^{ab}	-	-
Heavy	35.7^{e}	37.7^{bc}	37.7^{bc}	38.3^{a}	-	-
45 BWC[2]					0.04	<0.0001
Light	33.0^{g}	36.1^{ef}	35.8^{ef}	37.2^{cd}	-	-
Medium	35.4^{f}	37.4^{cd}	37.3^{d}	38.2^{ab}	-	-
Heavy	36.0^{e}	38.2^{ab}	37.7^{bc}	38.5^{a}	-	-
60 BWC[2]					0.04	<0.0001
Light	33.1^{h}	36.6^{efg}	36.1^{fg}	37.5^{cde}	-	-
Medium	36.0^{g}	37.9^{bcd}	37.6^{d}	38.4^{ab}	-	-
Heavy	36.6^{f}	38.5^{a}	38.2^{abc}	38.6^{a}	-	-
120 BWC[2]					0.04	<0.0001
Light	35.4^{f}	37.4^{e}	37.3^{e}	38.0^{cde}	-	-
Medium	37.7^{e}	38.5^{abc}	38.3^{bcd}	38.6^{ab}	-	-
Heavy	38.0^{de}	38.8^{a}	38.6^{ab}	38.7^{a}	-	-
1440 BWC[2]					0.04	0.0002
Light	38.1^{abc}	38.0^{c}	38.5^{abc}	38.4^{abc}	-	-
Medium	38.7^{ab}	38.7^{ab}	38.5^{bc}	38.6^{ab}	-	-
Heavy	38.7^{ab}	38.9^{a}	38.6^{ab}	38.8^{ab}	-	-

[a,b,c,d,e,f,g,h]For each time, means within the T x BWC interaction with differing superscripts differ, $P \leq 0.05$.

[1]Control = not dried; Desiccant = dried by coating with a desiccant; Warming Box = placed in a warming box for 30 min; Desiccant+Warming Box = dried by coating with a desiccant, then placed in a warming box for 30

[2]Light = <1.0 kg; Medium = 1.0 to 1.5 kg; Heavy = > 1.5 kg.

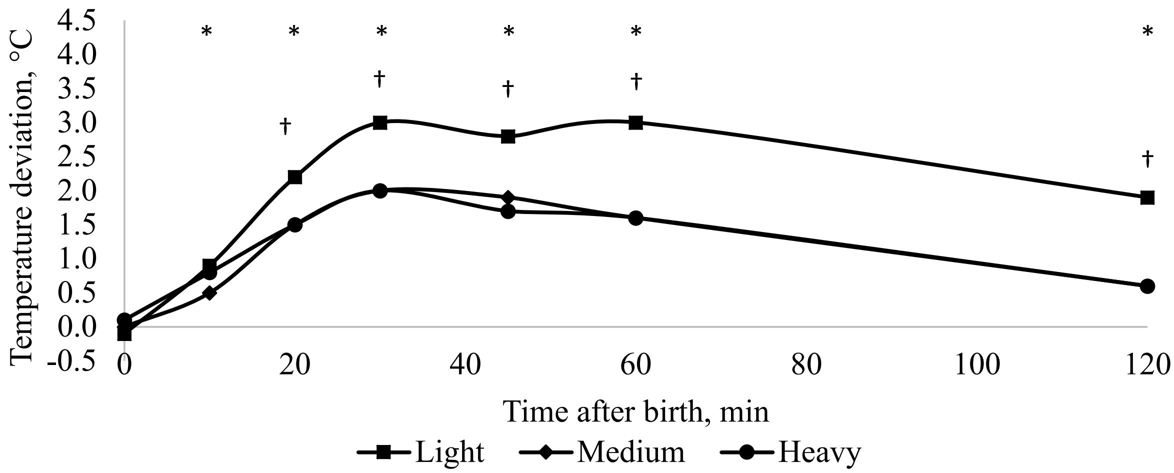
Figure 4.1a. Deviation in piglet rectal temperature between the Desiccant and Control treatments over the first 2 h after birth, for Light (< 1.0 kg), Medium (1.0 to 1.5 kg), and Heavy (> 1.5 kg) birth weight categories.



*Deviation to the Control treatment different to 0 for all birth weight categories, at $P \leq 0.05$.

†Difference in the magnitude of the deviation between treatments for Light and Medium birth weight categories, at $P \leq 0.05$. There were no differences ($P > 0.05$) between Medium and Heavy birth weight categories.

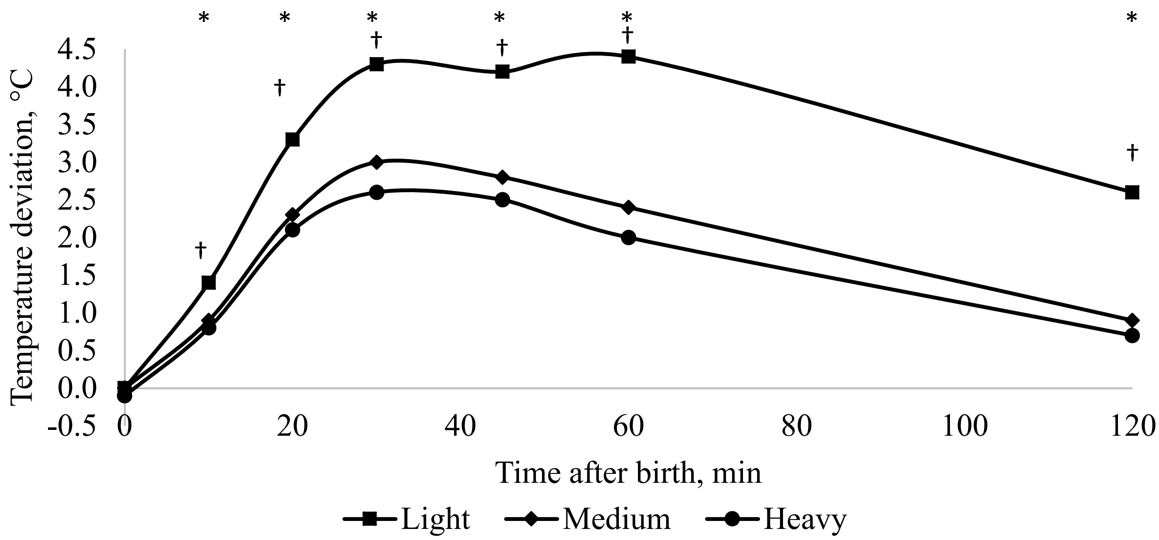
Figure 4.1b. Deviation in piglet rectal temperature between the Warming Box and Control treatments over the first 2 h after birth, for Light (< 1.0 kg), Medium (1.0 to 1.5 kg), and Heavy (> 1.5 kg) birth weight categories.



*Deviation to the Control treatment different to 0 for all birth weight categories, at $P \leq 0.05$.

†Difference in the magnitude of the deviation between treatments for Light and Medium birth weight categories, at $P \leq 0.05$. There were no differences ($P > 0.05$) between Medium and Heavy birth weight categories.

Figure 4.1c. Deviation in piglet rectal temperature between the Desiccant+Warming Box and Control treatments over the first 2 h after birth, for Light (< 1.0 kg), Medium (1.0 to 1.5 kg), and Heavy (> 1.5 kg) birth weight categories.



*Deviation to the Control treatment different to 0 for all birth weight categories, at $P \leq 0.05$.
†Difference in the magnitude of the deviation between treatments for Light and Medium birth weight categories, at $P \leq 0.05$. There were no differences ($P > 0.05$) between Medium and Heavy birth weight categories.

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CHAPTER 5: Effect of drying and/or warming piglets at birth under warm farrowing room temperatures on rectal temperature over the first 24 h after birth

Abstract

Piglets experience significant body heat loss immediately after birth, and drying and warming reduces this heat loss. However, these approaches may be less effective when farrowing room temperatures are relatively high (such as during summer). This study was carried out at a commercial facility to compare the effect of warming and drying piglets at birth on postnatal rectal temperature under relatively warm farrowing house conditions (26.6 ± 2.09°C). A completely randomized design was used with 45 sows/litters to compare three Intervention Treatments (applied at birth): Control (no treatment); Warming (piglets placed in a plastic box under a heat lamp for 30 min); Drying+Warming (dried with desiccant and placed in a plastic box under a heat lamp for 30 min). Temperatures in the warming boxes averaged 37.7 ± 2.75°C. At birth, piglets were weighed; rectal temperature was measured at 0, 10, 20, 30, 45, 60, 120, and 1440 min after birth. A blood sample was collected from piglets at 24 h after birth to measure plasma immunocrit concentration. Data were analyzed using PROC MIXED of SAS. Litter was the experimental unit; piglet was a subsample of litter. The model for piglet temperature included fixed effects of treatment, measurement time (repeated measure), the interaction, and the random effect of sow. Compared to the Control, temperatures were higher ($P \leq 0.05$) for the Warming treatment between 10 and 60 min and higher ($P \leq 0.05$) for the Drying+Warming treatment between 10 and 120 min after birth. Temperatures were also greater ($P \leq 0.05$) for the Drying+Warming than the Warming treatment between 20 and 120 min. Drying and warming had a larger positive effect on temperatures for low birth weight piglets (< 1.0 kg) compared to heavier littermates. The responses to drying and/or warming were generally

less than those observed in previous experiments with similar treatments carried out under cooler farrowing room conditions. Piglet immunocrit values were lower ($P \leq 0.05$) for the Drying+Warming treatment compared to the other two treatments, which were similar ($P > 0.05$). There was a trend ($P = 0.10$) for immunocrit values to be lower for light (< 1.0 kg) compared to heavier birth weight piglets. In conclusion, drying and warming piglets at birth was more effective for reducing rectal temperature decline than warming alone, though the effect was less than observed in previous studies carried out under cooler conditions.

Introduction

Farrowing facilities house both sows and piglets, which have markedly different thermal requirements. Newborn piglets have a high surface area to body volume ratio, little body surface insulation, and limited capacity for thermoregulatory heat production, resulting in a high critical temperature (around 35°C) and a relatively narrow thermoneutral zone (Mount, 1959). However, sows have a lower surface area to body volume ratio, greater body surface insulation, and greater heat production capacity, resulting in a substantially lower thermoneutral zone (15 to 20°C; Black et al., 1993). At higher temperatures (e.g., ≥ 25°C), sows show signs of heat stress including increased respiration rates and higher rectal temperatures, and experience longer farrowing duration (Muns et al., 2016). As a compromise between the thermal requirements of the sow and piglet, in commercial practice farrowing rooms are typically kept at temperatures around 22°C on the day of farrowing (PIC, 2018). At these temperatures, newborn piglets experience considerable heat loss from the body surface, partly due to convection and radiation, but also due to evaporation of amniotic fluids. Therefore, in the absence of any intervention, all piglets will experience some degree of chilling under typical commercial conditions (Vande Pol et al., 2020a,b). This predisposes piglets to mortality both directly due to hypothermia and from secondary causes such as starvation, crushing, and disease (Devillers et al., 2011). Low birth weight piglets are particularly at risk of hypothermia, as they have higher body surface to body volume ratios, and, therefore, a relatively greater potential to lose more heat than heavier littermates (Herpin et al., 2002).

One approach to limiting piglet heat loss without increasing farrowing room temperature is to provide a localized heated area in the farrowing pen, using, for example, heat lamps. While this is a common commercial practice, newborn piglets are generally not confined to the heated area, and are often more attracted to the sow in the first few days after birth (Houbak et al., 2006; Pedersen et al., 2006). Warming boxes (a box that includes a heat source) can be utilized to confine piglets to this heated area for short periods of time after birth (typically between 15 min and 2 h) to minimize heat loss. Another method of limiting early postnatal heat loss is through drying piglets at birth, thereby reducing evaporation and associated heat loss from the body surface. Vande Pol et al. (2020b) showed that both drying piglets with a desiccant and placing them in a warming box for 30 min after birth were similarly effective at reducing piglet temperature loss in the early postnatal period. However, the combination of these two approaches was more effective than either one separately.

Although both drying and warming of newborn piglets have been used in commercial practice, there has been little published research on the effects of these approaches, used either singly or in combination, on piglet temperatures during the early postnatal period. In addition, most published studies have been carried out with farrowing room temperatures between 18 and 22°C (e.g., Le Dividich and Noblet, 1981; Vande Pol et al., 2020a,b). However, temperatures in farrowing rooms can be considerably higher, particularly during the warmer periods of the year, often exceeding 28°C (Koketsu et al., 1996). These higher temperatures are likely to result in reduced heat loss from newborn piglets, and, therefore, it is important to determine whether piglet drying and/or warming is as effective at moderating postnatal temperature decline under such conditions.

Materials and Methods

This study was conducted in the farrowing facilities of a commercial breed-to-wean farm of The Maschhoffs, LLC, located near Crawfordsville, IN, during the months August and September. The experimental protocol was approved by the University of Illinois Institutional Animal Care and Use Committee prior to the initiation of the research.

Animals, Experimental Design, Treatments, and Allotment

A total of 45 sows and litters (603 piglets) were used in the study. Sows were from commercial dam lines of Yorkshire and Landrace origin that had been mated to commercial sire lines. A completely randomized design was used, with litter as the experimental unit and piglet as a sub-sample of the litter, and three Intervention Treatments (applied at birth): Control (no treatment); Warming (piglets placed in a plastic box under a heat lamp for 30 min; mean temperature in the box was 37.7 ± 2.69°C); Drying+Warming (piglets were dried by coating with a commercial cellulose-based desiccant until completely dry, then placed in a plastic box under a heat lamp for 30 min; mean temperature in the box was 37.6 ± 2.85°C). Sows/litters were randomly allotted to Intervention Treatments at the start of farrowing, with the restriction that dam genotype and parity were balanced across treatments.

Housing and Management

Each sow was housed in an individual farrowing crate, located in the center of a farrowing pen, which had either woven metal or perforated plastic flooring. Crate dimensions were 0.55 m by 1.95 m, giving a floor space within the crate of 1.07 m^2; pen dimensions were

1.52 m by 2.07 m, giving a total pen floor space of 3.15 m^2. Crates were equipped with a sow-operated feed dispenser attached to the feed trough, and a nipple-type water drinker for the sow. An infrared heat lamp was suspended in the center of the floor area on one side of the farrowing crate over an insulated rubber mat (average temperature under the heat lamp was 38.1 ± 3.13°C). For the Intervention Treatments that used a warming box, this heat lamp was suspended over a plastic box throughout the duration of farrowing. The piglets were placed in the warming box immediately after birth, removed after 30 min, and returned to the farrowing pen. Room temperature was maintained using fans and heaters; thermostats were set to 22.5°C throughout the study period.

Management in the farrowing facility was according to unit protocols, which were generally in line with standard commercial practices. Sows that had not farrowed by d 116 of gestation were induced to farrow on the following day using Lutalyse (1 injection of 1 mL given at 0600 h; Zoetis; Parsippany, NJ); the identity of each sow induced and date of induction were recorded. The farrowing process was monitored continuously by the investigators; if the interval between the births of piglets exceeded 60 min, the investigator checked the birth canal for obstructions, and assisted the farrowing process as needed.

Procedures and Measurements

Sow rectal temperature was measured at the start and end of the farrowing process, and sow parity and litter size were recorded. At birth, piglets were given a uniquely numbered ear tag for identification, treatments were applied, and piglet rectal temperature was measured at 0, 10, 20, 30, 45, 60, 120, and 1440 min after birth. After treatments were applied, piglets were returned to the farrowing pen (immediately for the Control and after 30 min in a warming box for the other two Intervention Treatments), being placed at the udder of the sow. Piglets were weighed within 12 h of birth using a Brecknell LPS-15 bench scale (Avery Weigh-Tronix; Fairmont, MN). Scales were calibrated daily prior to use with a standard test weight.

Piglet and sow rectal temperatures were measured using a HSTC-TT-K-24S-36 thermocouple attached via a SMPW-K-M connector to a dual input K/J digital thermometer (HH801A; Omega; Stamford, CT) at a depth of 2.5 cm and 10 cm, respectively. Thermometers were calibrated each week during the study period by taking measurements in a temperature-controlled chamber that was set at temperatures that encompassed the expected range (i.e., 30, 32, 34, 36, 38, and 40°C). A regression equation was developed between measured and set temperatures, and was used to adjust all rectal temperature measurements taken during the following week of the study period.

Farrowing room ambient temperature was measured continuously over the study period using data loggers [Temtop TemLog 20H (Elitech Technology; Silicon Valley, CA)]. The temperature in each farrowing pen at three locations [behind and at either side of the sow (one of these measurements being under the heat lamp)] was measured at the beginning and end of the farrowing process using a digital infrared thermometer [TOOGOO GM320 LCD digital infrared thermometer gun (Shenzhen IMC Digital Technology Co. Shenzhen, China)].

Blood samples to measure serum immunoglobulin immunocrit concentrations were obtained from a sub-sample of four piglets from each litter (one piglet randomly selected from each birth weight quartile of each litter). At 24 h after birth, a 2 ml blood sample was collected from the abdominal vein into plain glass tubes, placed immediately on ice, and subsequently centrifuged (for 30 minutes at 3000 × g). Plasma was obtained and stored at -20°C prior to analysis for immunoglobulin immunocrit concentration, which was carried out by Dr. Clay Lents and colleagues at a USDA laboratory (USDA Agricultural Research Service, Clay Center, NE).

Statistical Analysis

The litter of piglets was the experimental unit for all measurements; piglet was a sub-sample of litter. The PROC UNIVARIATE procedure of SAS (SAS Inst. Inc., Cary, NC) was used to verify normality and homogeneity of variances of the residuals. All variables conformed to the assumptions of normality and homogeneity and were analyzed using the PROC MIXED procedure of SAS (Littell et al., 1996). Data were analyzed as a completely randomized design; the model used for the analysis of sow and litter parameters accounted for the fixed effect of Intervention Treatment. The model used for analysis of treatment differences in piglet birth weight and serum immunoglobulin immunocrit concentration also included the random effect of sow/litter.

Treatment effects on piglet rectal temperatures at the various measurement times after birth were analyzed using a repeated measures analysis, with the model accounting for the fixed effects of Intervention Treatment, measurement time, and the interaction, and the random effect of piglet within litter. A repeated-measures statement was included in the model with measurement time as the REPEATED term and piglet as the SUBJECT term.

An analysis was carried out to determine if the response to Intervention Treatments differed according to piglet birth weight. Data were divided into Light (< 1.0 kg), Medium (1.0 to 1.5 kg), or Heavy (> 1.5 kg) birth weight categories (BWC). The maximum weight for the Light category (i.e., 1.0 kg) represented the birth weight below which pre-weaning mortality increases substantially (Zotti et al., 2017). The minimum weight for the Heavy category (i.e., 1.5 kg) represented the weight above which pre-weaning mortality is relatively unaffected by birth weight (Zotti et al., 2017). Piglet rectal temperature data at each measurement time were analyzed using a statistical model that included the fixed effects of BWC, Intervention Treatment, and the interaction, and the random effect of piglet within litter.

For all analyses, differences between least-squares means were separated using the PDIFF option of SAS, and differences were considered significant at $P \leq 0.05$.

Results and Discussion

Sow and litter parameters and farrowing pen temperatures have been summarized by Intervention Treatment in Table 5.1. There were no differences ($P > 0.05$) between treatments for any of these parameters or measurements. In general, the sows and litters used in the study were typical of U.S. commercial production. The majority of sows were between parities 1 and 8. Average number of piglets born alive per litter (12.9 to 14.3) were similar to values for U.S. herds reported at the time this study was conducted (13.2 piglets; PigChamp, 2018). Sow temperatures before and after farrowing averaged between 38.6 and 39.4°C, which is typical for farrowing sows (Littledike et al., 1979). Farrowing pen temperatures, which averaged between 25.1 and 28.2˚C (Table 5.1), were higher than the set point (22.5˚C). These temperatures were expected, as the study was conducted during the summer months when it was difficult to maintain farrowing room temperatures.

The least-squares means for the effects of drying and/or warming on piglet rectal temperature over the first 24 h after birth are presented in Table 5.2. Temperatures at birth were similar ($P > 0.05$) for the three Intervention Treatments and were within the range reported in previous research (i.e., between 37.0 and 41.5°C; Pomeroy, 1953; Kammersgaard et al., 2011; Vande Pol et al., 2020a,b). At 1440 min after birth, the Warming treatment resulted in a higher temperature ($P \leq 0.05$) than the Control, with the Drying+Warming treatment being intermediate ($P > 0.05$), however, treatment differences were relatively small (≤ 0.2°C). Most studies have shown that piglet temperatures approach levels observed at birth by 1440 min (McGinnis et al., 1981; Pattison et al., 1990; Xiong et al., 2018; Vande Pol et al., 2020a,b).

For the Control treatment, which provides an estimate of temperature changes in untreated piglets, the minimum temperature was at 30 min after birth (Table 5.2), which is in agreement with a number of studies that have measured temperature decline of untreated piglets (Anderson and Pedersen, 2015; Cooper et al., 2019; Vande Pol et al., 2020a,b). However, reported values for this minimum temperature have varied widely between studies, from 33.6°C (Xiong et al., 2018) to 36.6°C (Pattison et al., 1990). The minimum temperature observed for the Control treatment in the current study was greater than those found in previous research (e.g., Cooper et al., 2019; Vande Pol et al., 2020a,b), which was most likely because of the higher farrowing temperatures experienced during this study. However, despite these relatively high farrowing room temperatures, untreated piglets still experienced a considerable decline in rectal temperature.

Compared to the Control, temperatures were higher ($P \leq 0.05$) for the Warming treatment between 10 and 60 min and higher ($P \leq 0.05$) for the Drying+Warming treatment between 10 and 120 min (Table 5.2). Temperatures were also greater ($P \leq 0.05$) for the Drying+Warming than the Warming treatment between 20 and 120 min. Minimum temperatures for the Warming and Drying+Warming treatments were reached earlier than for the Control (at 20, 10, and 30 min after birth, respectively) and were higher (37.7, 38.1, 36.7°C, respectively). This suggests that warming piglets in a box under a heat lamp reduced the extent and duration of rectal temperature decline in the early postnatal period, but this approach was even more effective when combined with drying.

Published studies related to the effect of warming piglets at birth on postnatal temperature changes are limited in number and vary considerably in methodology. Some studies provided additional heat sources in the farrowing pen without confining piglets to the heated area, and these found relatively small effects on piglet temperatures (≤ 0.8°C at all measurement times within the first 24 h after birth; McGinnis et al., 1981; Vasdal et al., 2011; Andersen and Pedersen, 2015). Only three studies evaluated the effect of confining piglets to a localized heated area for a period of time after birth. Pedersen et al. (2016) and Vande Pol et al. (2020b) found that confining newborn piglets under a radiant heat source (at 34 to 36°C for 2 h and 30 min after birth, respectively), compared to those kept at a room temperature increased minimum rectal temperature by between 1.2 and 1.7°C. These responses are generally similar to those found in the current study. In contrast, Pattison et al. (1990) found a much smaller effect (0.3°C at 60 min after birth) of confining piglets to a heated creep area for 45 min. However, the warming treatment in that study started at 15 min after birth, which may explain the relatively limited response to warming, particularly given that all studies show that temperatures of untreated piglets decline rapidly after birth. The general conclusion from these studies is that confining piglets to a heated area immediately after birth was more effective at reducing postnatal temperature decline than adding a heat source to the farrowing pen without piglet confinement.

Although a number of studies have shown that drying of piglets at birth reduces the extent and duration of postnatal temperature decline (e.g., Berbigier et al., 1978; Cooper et al., 2019; Vande Pol et al., 2020a,b), only one study has evaluated the combination of drying and warming. Similar to the results of the current study, Vande Pol et al. (2020b) found that the combination of drying and warming was more effective at minimizing piglet postnatal temperature decline than either approach applied separately. However, these effects were relatively greater in the study of Vande Pol et al. (2020b) than in the current study. These two studies used the same three Intervention Treatments, and were carried out in the same facilities with similar methodology; however, the experiment of Vande Pol et al. (2020b) was carried out at a cooler time of year (February and March), when farrowing room temperatures were lower (21.8 ± 1.80°C) than in the current study (26.6 ± 2.09°C), which was carried out in August and September. Direct comparison of the results of these two studies allows for an indirect estimate of the effects of farrowing room temperature on the responses to drying and warming of piglets. Data from the two studies for the three common Intervention Treatments were combined, and treatment effects were determined within each measurement time using a statistical model that included the fixed effects of Farrowing Room Temperature (FRT; COOL vs. WARM for the data of Vande Pol et al., 2020b and the current study, respectively), Intervention Treatment, and the interaction, and the random effect of piglet within litter. Results of this analysis are presented in Table 5.3.

There were interactions ($P \leq 0.05$) between Intervention Treatment and FRT at all measurement times between 20 and 60 min after birth. The overall effects of the three Intervention Treatments were similar for both FRT at these times, with the Control treatment having the lowest ($P \leq 0.05$) and the Drying+Warming treatment having the highest ($P \leq 0.05$) temperatures. However, differences between the Control and the other two treatments were generally much greater under COOL than WARM conditions. This was in part due to the differences in piglet temperatures between the two FRT being much greater for the Control than the other two treatments. For example, temperatures for the Control treatment between 20 to 60 min after birth were between 1.2 to 1.5˚C greater ($P \leq 0.05$) under WARM than COOL FRT

(Table 5.3). In contrast, differences between the FRT at these times were much smaller for the other two treatments, ranging between 0.2 to 0.6˚C for the Warming and 0.2 to 0.3˚C for the Drying+Warming treatment, and were not always statistically significant ($P > 0.05$; Table 5.3). As a result, the difference between the Control and the other treatments was greater under COOL than WARM conditions. For example, at 30 min, the differences between the Control and Drying+Warming treatments was 2.9 and 1.6°C under COOL and WARM FRT, respectively (Table 5.3). This suggests that drying and warming piglets at birth was effective at reducing piglet postnatal temperature decline for both FRT, but the effect was much greater at the lower FRT, which would typical of the majority of the year. However, it should be borne in mind that this comparison is not a direct estimate of the effects of FRT *per se*. The two studies were carried out at different times of the same year, and a number of factors other than farrowing room temperature could have changed in the interim that may have influenced the responses of piglets to these Intervention Treatments. Further research is needed to directly establish the responses of piglets to drying and warming under differing farrowing conditions.

Although a number of studies have evaluated the effects of farrowing room temperatures on sow performance (e.g., Black et al., 1993; Koketsu et al., 1996; Muns et al., 2016), there has been limited research with piglets. Le Dividich and Noblet (1981) found that piglets kept in low (18 to 20°C) compared to high (30 to 32°C) farrowing pen temperatures had lower rectal temperatures at 20 min after birth (1.6°C). Pedersen et al. (2013) found that piglets in rooms at 25°C had higher rectal temperatures at 30 min after birth (0.9°C) than those in rooms at 15 or 20°C. Similarly, for the comparison between the current study and that of Vande Pol et al. (2020b), piglet rectal temperature on the Control treatment was 1.5°C higher at 30 min under WARM compared to COOL FRT (Table 5.3).

For the current study, the effects of drying and/or warming for piglets of differing birth weights were also evaluated. Least-squares means for Intervention Treatment by BWC interactions are presented in Table 5.4. There were interactions ($P \leq 0.05$) at all measurement times except at birth, when temperatures were similar ($P > 0.05$) for all BWC on all treatments. In addition, at 1440 min, temperature differences between the BWC across the three Intervention Treatments were relatively small (Table 5.4). At measurement times between 10 and 120 min, Light piglets had lower ($P \leq 0.05$) temperatures than Medium and Heavy piglets for all treatments, with the exception of the Drying+Warming treatment at 120 min, when temperatures of Light and Medium piglets were similar ($P > 0.05$; Table 5.4). Medium piglets had lower ($P \leq 0.05$) temperatures than Heavy between 10 and 120 min for the Control treatment, but only at 10 and 20 min for the other two treatments; at other measurement times the temperatures of these two BWC were similar ($P > 0.05$). A number of studies have also shown that low birth weight piglets experience a greater extent and duration of temperature decline after birth than heavier littermates (Pattison et al., 1990; Pedersen et al., 2016; Cooper et al., 2019; Vande Pol et al., 2020a,b).

The difference in temperature between BWC was generally greater for the Control than the other two Intervention Treatments (Table 5.4). For example, at 60 min after birth, the difference in temperature between Light and either Medium or Heavy piglets on the Control treatment was 2.4 and 3.2°C, respectively, compared to 1.3 and 1.5°C, respectively, for the Warming, and 1.1 and 1.3°C, respectively, for the Drying+Warming treatment. These results suggest that drying and warming of piglets at birth reduces the variation in postnatal temperature due to birth weight. In addition, the magnitude of the differences between the Control and the other treatments was generally greater for Light than for Medium or Heavy piglets (Table 5.4).

For example, at 45 min after birth, the difference in temperature between piglets on the Control and Drying+Warming treatment was 3.0, 1.6, and 1.0°C for Light, Medium, and Heavy piglets, respectively (Table 5.4). These results suggest that drying and warming piglets at birth minimized the extent of postnatal temperature decline in piglets of all birth weights, but was relatively more effective for lighter piglets.

The limited number of studies that have evaluated the effect of birth weight on the responses to drying and/or warming of piglets at birth have generally found similar results to the current experiment. Pedersen et al. (2016) found that adding a radiant heat source in the farrowing pen increased the average piglet temperature in the first 2 h after birth for piglets of all birth weights, with greater effects for lighter piglets. Vande Pol et al. (2020b) also reported that the effects of drying and warming were relatively greater in lighter piglets; however, the increases in temperature between dried and warmed compared to untreated piglets were greater than in the current study, which, as previously discussed, were most likely due to the differences in farrowing room temperatures experienced in the two studies.

Least-squares means for the effect of Intervention Treatment and BWC on plasma immunoglobulin immunocrit concentrations are presented in Table 5.5. Serum immunocrit concentration early after birth is an index of colostrum intake (Vallet et al., 2015). Immunocrit concentrations were higher ($P \leq 0.05$) for the Control and Warming treatments compared to the Drying+Warming treatment. The causes of these differences are not clear, and warrant further research. In addition, there was a trend ($P = 0.10$) for immunocrit values to be higher for Heavy compared to Light or Medium BWC piglets. These results suggest that drying and warming piglets at birth reduced colostrum intake and lighter birth weight piglets consume less colostrum than heavier littermates. This is in line with other studies that have evaluated the impact of birth weight on immunocrit concentrations (Devillers et al., 2011; Nguyen et al., 2013; Le Dividich et al., 2017) and also with those that have directly measured colostrum intake (Devillers et al., 2011; Le Dividich et al., 2017). There were no other studies found that evaluated the effects of drying or warming piglets at birth on immunocrit concentration.

In conclusion, the results of the current study confirm that piglet birth weight is an important factor influencing postnatal temperatures, with lower birth weight piglets experiencing the greatest extent and duration of temperature decline. Warming piglets at birth was effective at reducing piglet temperature decline in the early postnatal period, and the combination of drying and warming was more effective, especially for low birth weight piglets. The lower response in piglet postnatal temperature to warming and/or drying in this study as compared to previous literature may be related to the higher farrowing room temperatures; however, further research is required to validate this concept.

Tables

Table 5.1. Summary of sow and litter parameters and farrowing pen temperatures during the study by Intervention Treatment.

	Intervention Treatment[1]				
Item.	Control	Warming Box	Desiccant+Warming Box	SEM	*P*-value
Average sow parity	2.9	2.9	2.8	0.67	0.99
Number of sows by parity[2]					
Parity 1	4	4	2	-	-
Parity 2	2	3	4	-	-
Parity 3 and 4	3	2	3	-	-
Parity 5 to 8	5	6	6	-	-
Parity 9+	1	0	0	-	-
Number of piglets born alive					
Total	195	215	193	-	-
Average per litter	13.0	14.3	12.9	0.84	0.40
Piglet birth weight (born alive), kg	1.41	1.39	1.44	0.023	0.31
Sow rectal temperature, °C					
Start of farrowing	38.6	38.9	38.8	0.12	0.34
After farrowing	39.0	39.2	39.0	0.12	0.33
24 h after farrowing	39.4	39.4	39.1	0.16	0.40
Farrowing pen temperature, °C					
Before Farrowing					
Under heat lamp	37.3	36.8	36.8	0.66	0.82
Side of pen opposite heat lamp	25.8	25.4	26.2	0.51	0.54
Behind sow	25.4	25.1	25.9	0.45	0.40
After Farrowing					
Under heat lamp	38.8	38.4	38.5	0.82	0.92
Side of pen opposite heat lamp	27.7	27.7	28.2	0.51	0.79
Behind sow	27.2	27.0	27.5	0.50	0.77

[1]Control = no treatment; Warming Box = placed in a plastic box under a heat lamp for 30 min; Desiccant+Warming Box = dried with desiccant and placed in a plastic box under a heat lamp for 30 min.

[2]Parity = total number of litters including the one used in the study.

Table 5.2. Least-squares means for the effect of Intervention Treatment on the rectal temperature of piglets over the first 24 h after birth under WARM Farrowing Room Temperatures.

	Intervention Treatment[1]				
Item.	Control	Warming Box	Desiccant+Warming Box	SEM	*P*-value
Number of litters	15	15	15	-	-
Piglet rectal temperature, °C					
Time after birth, min					
0	39.1	39.1	39.0	0.04	0.33
10	37.4^{b}	37.9^{a}	38.1^{a}	0.04	<0.0001
20	36.8^{c}	37.7^{b}	38.1^{a}	0.04	<0.0001
30	36.7^{c}	37.8^{b}	38.3^{a}	0.04	<0.0001
45	36.9^{c}	37.7^{b}	38.4^{a}	0.04	<0.0001
60	37.3^{c}	37.9^{b}	38.6^{a}	0.04	<0.0001
120	38.1^{b}	38.4^{b}	38.7^{a}	0.04	<0.0001
1440	38.8^{b}	39.0^{a}	38.8^{ab}	0.04	0.02

[a,b,c]Within a row, means with differing superscripts differ at $P \leq 0.05$.

[1]Control = no treatment; Warming Box = placed in a plastic box under a heat lamp for 30 min; Desiccant+Warming Box = dried with desiccant and placed in a plastic box under a heat lamp for 30 min.

Table 5.3. Least-squares means for the interaction between Intervention Treatment and Farrowing Room Temperature (FRT) on postnatal rectal temperatures.

Item.	FRT[1]	Intervention Treatment[2] Control	Warming Box	Desiccant+Warming Box	SEM	*P*-value[3]
Piglet birth weight, kg	Cool	1.46	1.45	1.44	0.023	0.42
	Warm	1.41	1.39	1.44		
Piglet rectal temperature, °C						
Time after birth, min						
0	Cool	38.9	38.9	38.9	0.03	0.25
	Warm	39.1	39.1	39.0		
10	Cool	36.7	37.4	37.6	0.05	0.30
	Warm	37.4	37.9	38.1		
20	Cool	35.6[e]	37.0[c]	37.8[b]	0.06	<0.0001
	Warm	36.8[d]	37.7[b]	38.1[a]		
30	Cool	35.2[e]	37.2[c]	38.1[a]	0.07	<0.0001
	Warm	36.7[d]	37.8[b]	38.3[a]		
45	Cool	35.5[e]	37.3[c]	38.2[a]	0.08	<0.0001
	Warm	36.9[d]	37.7[b]	38.4[a]		
60	Cool	36.1[d]	37.7[b]	38.4[a]	0.09	<0.0001
	Warm	37.3[c]	37.9[b]	38.6[a]		
120	Cool	37.7	38.3	38.6	0.08	0.07
	Warm	38.1	38.4	38.7		
1440	Cool	38.7[bc]	38.6[c]	38.7[bc]	0.06	0.01
	Warm	38.8[bc]	39.0[a]	38.8[ab]		

[a,b,c,d,e] Within time of measurement, interaction means with differing superscripts differ at $P \leq 0.05$.
[1]Cool = January-March (farrowing room temperature 21.0 ± 1.65°C); Warm = August-September (farrowing room temperature 25.3 ± 1.67°C).

[2]Control = no treatment; Warming Box = placed in a plastic box under a heat lamp for 30 min; Desiccant+Warming Box = dried with desiccant and placed in a plastic box under a heat lamp for 30 min.
[3]*P*-value for the interaction between FRT and Intervention Treatments.

Table 5.4. Least-squares means for the interaction effects of Intervention Treatment (IT) and Birth Weight Category (BWC) on the rectal temperature of piglets over the first 24 h after birth.

	Intervention Treatment (IT)[1]				*P*-value
	Control	Warming Box	Desiccant+ Warming Box	SEM	BWC x IT Interaction
Number of litters					
Piglet rectal temperature, °C					
Time after birth, min					
0 BWC[2]				0.04	0.31
Light	38.9	39.0	38.7	-	-
Medium	39.1	39.2	39.1	-	-
Heavy	39.2	39.1	39.1	-	-
10 BWC[2]				0.04	<0.0001
Light	36.2^{g}	36.9^{f}	37.2^{ef}	-	-
Medium	37.4^{e}	37.9^{cd}	38.0^{bc}	-	-
Heavy	37.7^{d}	38.2^{ab}	38.4^{a}	-	-
20 BWC[2]				0.04	<0.0001
Light	35.2^{f}	36.6^{e}	37.3^{cde}	-	-
Medium	36.7^{e}	37.6^{c}	38.0^{b}	-	-
Heavy	37.3^{d}	38.1^{ab}	38.4^{a}	-	-
30 BWC[2]				0.04	<0.0001
Light	34.9^{f}	36.8^{de}	37.5^{cd}	-	-
Medium	36.6^{e}	37.8^{c}	38.3^{ab}	-	-
Heavy	37.3^{d}	38.1^{bc}	38.5^{a}	-	-
45 BWC[2]				0.04	<0.0001
Light	34.6^{f}	36.7^{de}	37.6^{cd}	-	-
Medium	36.8^{e}	37.8^{c}	38.4^{ab}	-	-
Heavy	37.6^{c}	38.0^{bc}	38.6^{a}	-	-
60 BWC[2]				0.04	<0.0001
Light	34.8^{e}	36.7^{d}	37.5^{cd}	-	-
Medium	37.2^{d}	38.0^{c}	38.6^{ab}	-	-
Heavy	38.0^{c}	38.2^{bc}	38.8^{a}	-	-
120 BWC[2]				0.04	<0.0001
Light	35.7^{e}	37.5^{d}	38.0^{bcd}	-	-
Medium	38.1^{cd}	38.4^{abc}	38.8^{ab}	-	-
Heavy	38.6^{ab}	38.6^{ab}	38.8^{a}	-	-
1440 BWC[2]				0.05	0.01
Light	38.4^{bc}	38.5^{c}	38.7^{abc}	-	-
Medium	38.8^{c}	39.1^{ab}	38.8^{abc}	-	-
Heavy	38.8^{abc}	39.1^{a}	38.9^{abc}	-	-

[a,b,c,d,e,f,g]For each time after birth, means within the Intervention Treatment by BWC interaction with differing superscripts differ at $P \leq 0.05$.

[1]Control = no treatment; Warming Box = placed in a plastic box under a heat lamp for 30 min; Desiccant+Warming Box = dried with desiccant, placed in a plastic box under a heat lamp for 30 min.

[2]Light = <1.0 kg; Medium = 1.0 to 1.5 kg; Heavy = > 1.5 kg.

Table 5.5. Least-squares means for the effect of Intervention Treatment and birth weight category on immunoglobulin immunocrit values at 24 h after birth.

	Intervention Treatment[1]					Birth Weight Category[2]				
Item.	Control	Warming	Drying+ Warming	SEM	*P*-value	Light	Medium	Heavy	SEM	*P*-value
Number of samples	54	56	55	-	-	15	80	70	-	-
Birth weight, kg	1.44	1.47	1.45	0.055	0.93	0.88	1.31	1.75	0.027	<0.0001
Immunoglobulin immunocrit, %[3]	13.1[a]	13.2[a]	11.7[b]	0.42	0.03	12.0	12.3	13.3	0.51	0.10

[1]Control = Piglets were not dried. Warming = Piglets were placed in a warming box for 30 minutes after birth. Drying+Warming = Piglets were dried at birth by coating with a desiccant, then placed in a warming box for 30 minutes.
[2]Light = <1.0 kg; Medium = 1.0 to 1.5 kg; Heavy = > 1.5 kg.
[3]Blood samples obtained at 24 h after birth on a sub-sample of four piglets per litter, one from each birth weight quartile.

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CHAPTER 6: Effect of providing supplemental oxygen to piglets at birth on rectal temperature over the first 24 h after birth

Abstract

Piglets experience a rapid decrease in body temperature immediately after birth, increasing the risk of mortality. The objective of this study was to determine the effect of providing supplemental oxygen to piglets at birth on rectal temperature over the first 24 h after birth. The study was carried out at a commercial sow facility using a completely randomized design with three Intervention Treatments (applied to piglets at birth): Control (no drying or supplemental oxygen); Desiccant (dried using a desiccant; no supplemental oxygen); Oxygen Chamber (dried using a desiccant and placed in a chamber at 40% oxygen for 20 min). A total of 42 litters (485 piglets) were randomly allotted to an Intervention Treatment at the birth of the first piglet. At birth, each piglet was identified with a numbered ear tag and weighed; rectal temperature was measured at 0, 20, 30, 45, 60, 120, and 1440 min after birth. Data were analyzed using a repeated measures model using PROC MIXED of SAS. Litter was the experimental unit, piglet was a subsample of the litter; the model included the fixed effects of Intervention Treatment, time (the repeated measure), and the interaction. Rectal temperatures at birth and 1440 min after birth were similar ($P > 0.05$) for all Intervention Treatments. At all measurement times between 20 and 60 min after birth, Control piglets had lower ($P \leq 0.05$) temperatures than those on the Desiccant treatment, with the Oxygen Chamber treatment being intermediate ($P \leq 0.05$). At 120 min after birth, the Control continued to have a lower ($P \leq 0.05$) temperatures than the Desiccant and Oxygen Chamber treatments, which were similar ($P > 0.05$). In addition, there were Intervention Treatment by birth weight interactions ($P \leq 0.05$) at all measurement times except birth and 1440 min after birth. Light (< 1.0 kg) piglets had lower ($P \leq$

0.05) temperatures than Medium (1.0 to 1.5 kg) or Heavy (1.5 to 2.0 kg) piglets between 20 and 60 min after birth on all treatments. However, Medium piglets had lower ($P \leq 0.05$) temperatures than Heavy on the Control, but not the other two treatments ($P > 0.05$). In addition, the increase in temperature for the Desiccant treatment compared to the Control was greater for Light piglets than for Medium or Heavy. This same general trend was observed for the Oxygen Chamber treatment, but differences relative to the Control were smaller within birth weight categories. In conclusion, drying piglets at birth increased rectal temperatures between 20 and 120 min after birth compared to an undried Control, especially for low birth weight piglets. However, the combination of drying and supplemental oxygen was less effective than drying alone.

Introduction

Piglets are born with little body surface insulation (limited subcutaneous body fat and a sparce hair coat), and low body energy reserves for thermoregulation. This results in a high critical temperature (below which the piglet needs to produce additional heat to maintain body temperature) of around 35°C (Mount, 1959). Due to their greater body size, sows have a lower thermal comfort zone (Black et al., 1993), above which they experience heat stress during farrowing (Muns et al., 2016). Therefore, farrowing rooms are typically kept at temperatures considerably below the piglets' critical temperature. As a result, piglets experience temperatures which lead to considerable heat loss (via convection and radiation) from the body surface. In addition, piglets are born wet with amniotic fluid and experience heat loss due to evaporation. In the absence of any intervention to reduce heat loss, all piglets will experience some degree of hypothermia under typical farrowing room conditions (Pedersen et al., 2011). Piglets that experience significant levels of hypothermia have decreased mobility and vigor, and are less able to compete with littermates for teat access during suckling, which reduces colostrum intake (Le Dividich and Noblet; 1981). Therefore, hypothermia predisposes piglets to mortality directly and from secondary causes such as starvation, disease, and crushing (Devillers et al., 2011). Low birth weight piglets are at a greater risk of early postnatal hypothermia compared to heavier littermates due to their greater surface area to body volume ratio (Herpin et al., 2002).

One method of reducing this early postnatal heat loss is through limiting evaporation of the amniotic fluid by drying piglets at birth. In this regard, Vande Pol et al. (2020a,b) showed that drying piglets with a desiccant reduced piglet temperature loss in the early postnatal period compared to an undried control, and this effect was greatest for low birth weight piglets. Another common cause of early postnatal piglet morbidity and mortality is asphyxiation due to extended time in the birth canal after the umbilical cord is ruptured (Trujillo-Ortega et al., 2007). One potential intervention to reduce the negative effects of asphyxiation is to administer oxygen to piglets after birth. However, there has been very limited research evaluating the effects of this intervention on either piglet body temperature or pre-weaning mortality. Herpin et al. (2001) found a positive effect of oxygen administration at birth (40% concentration for 20 min) to piglets for body temperature of all piglets, and for pre-weaning mortality of low birth weight piglets (1.0 to 1.4 kg). However, in contrast, Willard (2020) found that piglets that were dried with a desiccant and given supplemental oxygen at birth (40% concentration for 20 min) had lower temperatures than those that were dried without supplemental oxygen. Further research is necessary to determine the impact of oxygenation on postnatal changes in piglet body temperature. Therefore, the objective of this study was to determine the effects of drying and oxygen supplementation of piglets at birth on rectal temperatures over the first 24 h after birth.

Materials and Methods

This study was conducted in the farrowing facilities of a commercial breed-to-wean farm of The Maschhoffs, LLC, located near Crawfordsville, IN during the months of September through November, 2018. The experimental protocol was approved by the University of Illinois Institutional Animal Care and Use Committee prior to the initiation of the research.

Animals, Experimental Design, Treatments, and Allotment

A total of 42 litters (485 piglets) were used in the study. Sows were from commercial dam lines of Yorkshire and Landrace origin that had been mated to commercial sire lines. The study used a completely randomized design, with litter as the experimental unit (14 litters per treatment) and piglet as a sub-sample of the litter, to compare three Intervention Treatments (applied at birth): Control (no drying or supplemental oxygen); Desiccant (piglets were completely dried by repeatedly coating with a commercial cellulose-based desiccant); Oxygen Chamber (piglets were dried as in the Desiccant treatment and placed in a plastic box with a 40% oxygen concentration for 20 min). Litters were randomly allotted to an Intervention Treatment at the start of farrowing after the birth of the first piglet, with the restriction that dam genotype and parity were balanced across treatments.

Housing and Management

Sows were housed in individual farrowing crates, each located within a farrowing pen which had either woven metal or perforated plastic flooring. Crate dimensions were 0.55 m by 1.95 m, giving a floor space within the crate of 1.07 m^2; pen dimensions were 1.52 m by 2.07 m, giving a total pen floor space of 3.15 m^2. Crates were equipped with a sow-operated feed dispenser attached to a feed trough, and a nipple-type water drinker for the sow. An infrared heat lamp was suspended over an insulated rubber mat located in the center of the floor area on one side of the farrowing pen (average temperature under the heat lamp was 36.1 ± 3.15°C). Thermostats to maintain farrowing room temperature were set to 22.5°C throughout the study period, and temperatures were regulated using fans and heaters.

Management in the farrowing facility was according to unit protocols, which were generally in line with standard commercial practices. Sows that had not farrowed by 116 d of gestation were induced to farrow on the following day using Lutalyse (1 injection of 1 mL given at 0600 h; Zoetis; Parsippany, NJ); the identity of each sow induced and date of induction were recorded. The farrowing process was monitored continuously by the investigators; if the interval between the births of piglets exceeded 60 min, the investigator checked the birth canal for obstructions, and assisted the farrowing process as needed.

Procedures and Measurements

Piglet and sow rectal temperatures were measured using a HSTC-TT-K-24S-36 thermocouple attached via a SMPW-K-M connector to a dual input K/J digital thermometer (HH801A; Omega; Stamford, CT). A different thermocouple was used for the piglets and the sows. Thermometers were calibrated each week during the study period by taking measurements in a temperature-controlled chamber that was set at temperatures that encompassed the expected range (i.e., 30, 32, 34, 36, 38, and 40°C). Measured and set temperatures were used to develop regression equations for both sow and piglet thermocouples, and all rectal temperature measurements taken during the following week of the study period were adjusted using these regression equations.

Sow rectal temperature was measured (at a depth of 10 cm) at the start and end of the farrowing process and at 24 h after farrowing. Piglet rectal temperature (at a depth of 2.5 cm) was measured at birth, piglets were given a uniquely numbered ear tag for identification, and treatments were applied. Piglet temperatures were also measured at 20, 30, 45, 60, 120, and 1440 min after birth. After treatments were completed (immediately for the Control and Desiccant treatments and after 20 min for the Oxygen Chamber treatment), piglets were returned to the farrowing pen, being placed at the udder of the sow. Piglets were weighed on the day of birth using a Brecknell LPS-15 bench scale (Avery Weigh-Tronix; Fairmont, MN). Scales were calibrated daily prior to use with a standard test weight. Ambient temperatures in each farrowing pen [behind and at either side of the sow (one of these measurements being under the heat lamp)] were measured at the beginning and end of the farrowing process using a digital infrared thermometer [TOOGOO GM320 LCD digital infrared thermometer gun (Shenzhen IMC Digital Technology Co.; Shenzhen, China)].

The chambers used for the Oxygen Chamber treatment were constructed from a Contico rolling toolbox (dimensions 43.2 cm x 81.3 cm x 31.1 cm; Contico; Saint Louis, MO). Modifications were made to the box for the installation of the tubing to deliver oxygen, sensors, heating pad, and viewing windows (clear plastic ports on the top of the box for observing piglets). Oxygen concentrations in the chamber were monitored continuously using an oxygen monitor (CM-0161 TR250Z 95% Oxygen Sensor, CO2Meter, Ormond Beach, FL). A 50:50 oxygen:nitrogen mixture was flowed into the chamber to maintain oxygen concentration of around 40%.

Statistical Analysis

The litter of piglets was the experimental unit for all measurements; piglet was a sub-sample of litter. The PROC UNIVARIATE procedure of SAS (SAS Inst. Inc., Cary, NC) was used to verify normality and homogeneity of variances of the residuals. All variables conformed to the assumptions of normality and homogeneity and were analyzed using the PROC MIXED procedure of SAS (Littell et al., 1996). The study was carried out using a completely randomized design; the model used for the analysis of sow parameters and litter measurements accounted for the fixed effect of Intervention Treatment. The model used for analysis of differences between Intervention Treatments for piglet birth weight also included the random effect of piglet within litter.

Intervention Treatment effects on piglet rectal temperatures were analyzed using a repeated measures analysis, with the model accounting for the fixed effects of Intervention Treatment, measurement time, and the interaction, and the random effect of piglet within litter. A repeated-measures statement was included in the model with measurement time as the REPEATED term and piglet as the SUBJECT term.

An analysis was carried out to determine if the response to Intervention Treatments differed according to piglet birth weight. The data set was divided into three Birth Weight Categories: Light (< 1.0 kg), Medium (1.0 to 1.5 kg), or Heavy (> 1.5 kg). The maximum weight for the Light category (i.e., 1.0 kg) represented the birth weight below which pre-weaning mortality increases substantially (Zotti et al., 2017). The minimum weight for the Heavy category (i.e., 1.5 kg) represented the weight above which pre-weaning mortality is relatively unaffected by birth weight (Zotti et al., 2017). Piglet rectal temperature data at each measurement time were analyzed using a statistical model that included the fixed effects of Birth Weight Category, Intervention Treatment, and the interaction, and the random effect of piglet within litter.

For all analyses, differences between least-squares means were separated using the PDIFF option of SAS, and differences were considered significant at $P \leq 0.05$. All P-values were adjusted using a Tukey's adjustment for multiple comparisons.

Results and Discussion

Sow parameters and farrowing pen temperatures have been summarized by Intervention Treatment in Table 6.1. There were no differences ($P > 0.05$) between Intervention Treatments for any of the parameters or measurements. In general, the sows used in the study and the temperature conditions in the farrowing facilities were typical of U.S. commercial production. The majority of sows on the study were between parities 2 and 8. Average sow temperatures before and after farrowing were between 38.2 and 38.7°C, which is typical for farrowing sows (Littledike et al., 1979). Average farrowing room temperatures (between 21.4 and 22.7°C; Table 6.1) were close to the set point (22.5°C). Average temperatures under the heat lamps (between 34.6 and 35.9°C) were close to the target temperature (35°C), which was set to be similar to the critical temperature of newborn piglets (Mount, 1959). Oxygen concentration in the Oxygen Chamber treatment was similar to the target (40%), and temperatures were marginally lower than those in the farrowing pen away from the heat lamp (Table 6.1).

Effect of Treatments on the Temperature Decline of Piglets

Least-squares means for the effect of Intervention Treatment on litter size, piglet birth weight, and piglet rectal temperature over the first 24 h after birth are presented in Table 6.2. Litter sizes and birth weights were similar ($P \leq 0.05$) for the three Intervention Treatments (Table 6.2). The number of piglets born alive (10.7 to 12.2/litter) were comparable to values for U.S. herds reported by PigChamp at the time that this study was conducted (13.2 piglets/litter; 2017, 2018). Piglet birth weights were similar to those reported in recent studies (e.g., Feldspausch et al., 2019; Vande Pol et al., 2020a,b,c).

There was no effect ($P > 0.05$) of Intervention Treatment on rectal temperatures at birth (Table 6.2) with the means for all treatments being the same (Table 6.2). This was expected, as birth temperatures were taken before the treatments were applied. These birth temperatures were generally similar to those reported in previous research, which range from 37.0°C (Kammersgaard et al., 2011) to 40.5°C (Pomeroy, 1953). In addition, Kammersgaard et al. (2011) found considerable variation within the same study (between 37.0 and 41.5°C). Piglet temperatures decline rapidly after birth (Table 6.2), and variation between studies for birth temperature may reflect differing times of measurement relative to the time of birth.

The decline in rectal temperature of Control piglets after birth, which provides an estimate of changes experienced by undried piglets, was extensive, with the minimum temperature (at 30 min) being 3.0°C lower than at birth (Table 6.2). Subsequently, temperatures increased and approached the level observed at birth by 1440 min. These results are similar to a number of other studies, which also found that the minimum temperature of untreated piglets occurred at 30 min after birth (e.g. Xiong et al., 2018; Vande Pol et al., 2020a,b,c). However, mean temperatures at this time varied between studies, ranging from 33.6°C (Xiong et al., 2018) to 36.6°C (Pattison et al., 1990). Most studies have found that, on average, temperatures reach levels close to those at birth by 24 h after birth (McGinnis et al., 1981; Xiong et al., 2018; Vande Pol et al., 2020a,b,c).

Rectal temperatures were higher ($P \leq 0.05$) for the Desiccant than the Control treatment between 20 and 120 min after birth, with the differences generally being similar to those observed in previous studies that compared these two treatments (Vande Pol et al., 2020a,b,c). Minimum temperatures of piglets on the Desiccant treatment occurred earlier and were higher ($P \leq 0.05$) than those on the Control (Table 6.2). While drying of piglets at birth has been used in commercial production, there has been limited research for the effect of this intervention on piglet temperatures. Most studies have shown that drying reduced the extent of piglet temperature decline in the first 60 min after birth; however, the magnitude of the effect varied between studies. This may in part be due to the use of different drying materials and/or the timing of measurement of rectal temperature after birth (e.g., Berbigier et al., 1978; McGinnis et al., 1981). However, studies have also shown variation in the effectiveness of using a desiccant as the drying agent for reducing postnatal temperature decline. Vande Pol et al. (2020b) and Cooper et al. (2019) found that the maximum difference in temperature between undried piglets and those dried with a desiccant was at 45 min and was 2.2 and 2.4°C, respectively. Similarly, the current study found the greatest difference at 30 and 45 min (2.1°C; Table 6.2). In contrast, Vande Pol et al. (2020a) found the greatest difference was at 60 min (1.4°C). These differences may be in part due to differences in study conditions, such as farrowing room temperature (Vande Pol et al., 2020c).

Piglets on the Oxygen Chamber treatment also had higher ($P \leq 0.05$) rectal temperatures than the Control between 20 and 120 min after birth (Table 6.2). However, piglet rectal temperatures for the Oxygen Chamber treatment were lower ($P \leq 0.05$) than those for the Desiccant treatment from 20 min (when the piglets were removed from the oxygen chamber) to 60 min after birth. These results suggest that the combination of drying and oxygen administration was not as effective at reducing the extent of rectal temperature decline as drying alone. There has been very limited research for the effect of oxygenation on piglet rectal temperatures with which to compare these results. Similar to the current study, Willard (2020) found that the addition of supplemental oxygen (40% concentration for 20 min) resulted in lower piglet rectal temperatures between 20 and 60 min after birth compared to those that were only dried with a desiccant. In addition, the study of Willard (2020) found that placing dried piglets in a chamber at ambient oxygen concentration resulted in similar temperatures to the oxygenated treatment. This suggests that placing piglets in the chamber was the most likely cause of the observed temperature differences rather than the oxygen supplementation *per se*. In contrast, Herpin et al. (2001) reported a positive effect of providing supplemental oxygen (40% concentration for 20 min) to dried piglets on piglet rectal temperature at 30 min after birth. Herpin et al. (2001) also found reduced mortality for low birth weight piglets that were given supplemental oxygen, and this possible effect warrants further research.

Effect of Piglet Birth Weight on Responses to Treatments

Least-squares means for the Intervention Treatment by Birth Weight Category interaction are presented in Table 6.3. There were interactions ($P \leq 0.05$) at all measurement times except at birth and 1440 min after birth. At all other measurement times and for all Intervention Treatments, Light piglets had lower ($P \leq 0.05$) temperatures than the other Birth Weight Categories, with the exception of the Desiccant treatment at 120 min. Medium piglets had lower temperatures than Heavy ($P \leq 0.05$) at all times between 10 and 120 min for the Control treatment, but only at 20 min for the Oxygen Chamber treatment (Table 6.3). At all other times for the Oxygen Chamber treatment and at all times for the Desiccant treatment, there were no differences ($P > 0.05$) between temperatures of Medium and Heavy piglets. Previous research has also shown that, independent of intervention treatment, the extent and duration of piglet temperature decline after birth is greater in low birth weight piglets than in heavier littermates (Pattison et al., 1990; Pedersen et al., 2016; Cooper et al., 2019; Vande Pol et al., 2020a,b,c).

The Intervention Treatment by Birth Weight Category interactions were largely due to differences in the magnitude of treatment effects within each Birth Weight Category. Piglets of all Birth Weight Categories on the Desiccant and Oxygen Chamber treatments had higher ($P \leq$ 0.05) temperatures than those of similar weight on the Control between 20 and 60 min after birth

(Table 6.3). For example, the difference between the Control and Desiccant treatments at 30 min after birth were 3.2, 2.2, and 1.8°C for Light, Medium, and Heavy piglets, respectively. In addition, supplemental oxygen reduced this effect for piglets of all birth weights. For example, at 30 min after birth, the differences between the Control and Oxygen Chamber treatments were 1.8, 1.5, and 1.4°C. These results suggest that drying reduced the extent and duration of temperature decline for piglets of all birth weights, but had a greater effect for those of low birth weight, and the oxygenation treatment reduced this effect, particularly for low birth weight piglets.

Similar to the current study, Vande Pol et al. (2020a,b) and Willard (2020) found that drying piglets at birth with a desiccant reduced the magnitude and duration of temperature decline to a greater extent in lower compared to heavier birth weight piglets. There has been very limited research on the effects of oxygenation on piglet temperature, and the only study that evaluated potential interactions with piglet birth weight was that of Willard (2020). Similar to the current study, Willard (2020) found that supplemental oxygen reduced piglet temperatures compared to drying alone at all times and for all birth weights at 30 min after birth, and that low birth weight piglets (< 1.0 kg) were more affected.

In conclusion, the results of the current study confirm that birth weight is an important factor influencing piglet temperatures in the early postnatal period, with lower birth weight piglets experiencing the greatest extent and duration of temperature decline. Drying piglets at birth increased piglet temperatures, particularly for low birth weight piglets. The oxygenation treatment used in this study reduced this effect, with a greater negative effect for light piglets. Further research is necessary to determine the possible effects of oxygenation on piglet pre-weaning mortality.

Tables

Table 6.1. Summary of sow parity and rectal temperature and farrowing pen temperatures during the study by Intervention Treatment.

	Intervention Treatment[1]				
Item.	Control	Desiccant	Oxygen Chamber		*P*-value
Average sow parity	3.6	3.5	2.9	0.80	0.80
Number of sows by parity[2]					
Parity 1	4	4	4	-	-
Parity 2	0	2	2	-	-
Parity 3 and 4	2	1	3	-	-
Parity 5 to 8	6	4	4	-	-
Parity 9+	2	3	1	-	-
Sow rectal temperature, °C					
Start of farrowing	38.5	38.6	38.6	0.15	0.91
After farrowing	39.1	39.1	39.3	0.13	0.33
24 h after farrowing	39.2	39.5	39.1	0.15	0.17
Farrowing pen temperature, °C					
Before Farrowing					
Under heat lamp	35.5	36.8	35.2	0.91	0.40
Side of pen opposite heat lamp	25.3	25.3	25.4	0.65	0.99
Behind sow	25.4	25.2	24.7	0.60	0.71
After Farrowing					
Under heat lamp	36.1	35.8	36.2	0.63	0.88
Side of pen opposite heat lamp	26.1	26.1	27.0	0.67	0.55
Behind sow	25.5	25.9	26.1	0.63	0.77
Oxygen concentration	-	-	40.4 (2.83)[3]	-	-
Temperature in oxygen chamber	-	-	24.4 (4.40)[3]	-	-

[1]Control = piglets were not dried; Desiccant = piglets were dried at birth by coating with a desiccant; Oxygen Chamber = piglets were dried at birth by coating with a desiccant, then placed in a box at 40% oxygen for 20 min.

[2]Parity = total number of litters including the one used in the study.
[3]Mean (standard deviation).

Table 6.2. Least-squares means for the effect of Intervention Treatment on the rectal temperature of piglets over the first 24 h after birth.

	Intervention Treatment[1]				
	Control	Desiccant	Oxygen Chamber	SEM	*P*-value
Number of litters	14	14	14	-	-
Number of piglets born alive					
Total	150	164	171	-	-
Average per litter	10.7	11.7	12.2	0.84	0.45
Piglet birth weight (born alive), kg	1.44	1.45	1.41	0.027	0.60
Piglet rectal temperature, °C					
Time after birth, min					
0	38.8	38.8	38.8	0.04	0.78
20	36.0^{c}	37.6^{a}	37.2^{b}	0.04	<0.0001
30	35.8^{c}	37.9^{a}	37.3^{b}	0.04	<0.0001
45	36.1^{c}	38.2^{a}	37.7^{b}	0.04	<0.0001
60	36.6^{c}	38.4^{a}	38.1^{b}	0.04	<0.0001
120	37.9^{b}	38.6^{a}	38.7^{a}	0.04	<0.0001
1440	39.0	39.0	38.8	0.04	0.30

[a,b,c]Within a row, means with differing superscripts differ at $P \leq 0.05$.

[1]Control = piglets were not dried; Desiccant = piglets were dried at birth by coating with a desiccant; Oxygen Chamber = piglets were dried at birth by coating with a desiccant, then placed in a box at 40% oxygen for 20 min.

Table 6.3. Least-squares means for the interaction of Intervention Treatment (IT) and Birth Weight Category (BWC) on the rectal temperature of piglets over the first 24 h after birth.

		Intervention Treatment (IT)[1]				*P*-value
Item.		Control	Desiccant	Oxygen Chamber	SEM	BWC x IT Interaction
Number of piglets born alive						
Light		22	17	17	-	-
Medium		49	75	85	-	-
Heavy		79	72	69	-	-
Piglet rectal temperature, °C						
Time after birth, min						
0	BWC[2]				0.13	0.12
	Light	38.7	38.7	38.5	-	-
	Medium	38.7	38.8	38.8	-	-
	Heavy	38.8	38.8	38.9	-	-
20	BWC[2]				0.18	0.01
	Light	34.5^{f}	36.7^{cd}	35.9^{de}	-	-
	Medium	35.9^{d}	37.6^{ab}	37.1^{bc}	-	-
	Heavy	36.5^{ce}	37.8^{a}	37.6^{a}	-	-
30	BWC[2]				0.2	0.001
	Light	33.9^{h}	37.1^{cde}	35.7^{fg}	-	-
	Medium	35.7^{g}	37.9^{ab}	37.2^{bcd}	-	-
	Heavy	36.4^{ef}	38.2^{a}	37.8^{abc}	-	-
45	BWC[2]				0.22	0.01
	Light	34.1^{e}	37.3^{bc}	36.1^{cd}	-	-
	Medium	35.9^{d}	38.2^{a}	37.7^{ab}	-	-
	Heavy	36.7^{c}	38.5^{a}	38.1^{ab}	-	-
60	BWC[2]				0.23	<0.0001
	Light	34.2^{e}	37.7^{bc}	36.5^{cd}	-	-
	Medium	36.4^{d}	38.5^{a}	38.1^{ab}	-	-
	Heavy	37.3^{c}	38.6^{a}	38.5^{ab}	-	-
120	BWC[2]				0.17	0.0002
	Light	36.8^{c}	38.2^{ab}	37.2^{bc}	-	-
	Medium	37.7^{b}	38.7^{a}	38.7^{a}	-	-
	Heavy	38.3^{a}	38.7^{a}	38.9^{a}	-	-
1440	BWC[2]				0.14	0.17
	Light	38.7	38.9	38.3	-	-
	Medium	39.0	39.1	38.8	-	-
	Heavy	39.1	39.0	38.9	-	-

[a,b,c,d,e,f,g,h]For each time, means within the IT x BWC interaction with differing superscripts differ, $P \leq 0.05$.

[1]Control = piglets were not dried; Desiccant = piglets were dried at birth by coating with a desiccant; Oxygen Chamber = piglets were dried at birth by coating with a desiccant, then placed in a box at 40% oxygen for 20 min.

[2]Light = <1.0 kg; Medium = 1.0 to 1.5 kg; Heavy = > 1.5 kg.

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CHAPTER 7: Effect of drying and warming piglets at birth on pre-weaning mortality

Abstract

Piglets are susceptible to hypothermia early after birth, which is a major pre-disposing factor for pre-weaning mortality (PWM). Drying and warming piglets at birth has been shown to reduce early postnatal temperature decline. This study evaluated the effect of drying and warming piglets at birth on PWM and weaning weight (WW) under commercial conditions. A completely randomized design was used with 802 sows/litters (10327 piglets); sows/litters were randomly allotted at start of farrowing to one of two Intervention Treatments (applied at birth): Control (no drying or warming); Drying+Warming (dried with a cellulose-based desiccant and placed in a box under a heat lamp for 30 min). Piglets were weighed at birth and weaning; PWM was recorded. Rectal temperature was measured at 0 and 30 min after birth on all piglets in a sub-sample of 10% of litters. The effect of Farrowing Pen Temperature (FPT) on WW and PWM was evaluated by comparing litters born under COOL (< 25°C) to those born under WARM (≥ 25°C) conditions. The effect of birth weight on WW and PWM were evaluated by comparing three Birth Weight Categories (BWC; Light: < 1.0 kg, Medium: 1.0 to 1.5 kg, or Heavy: > 1.5 kg). PROC GLIMMIX and MIXED of SAS were used to analyze mortality and other data, respectively. Litter was the experimental unit; piglet a subsample of litter. The model included fixed effects of Intervention Treatment, and FPT or BWC as appropriate, the interaction, and the random effects of litter. Rectal temperature at 30 min after birth was greater ($P \leq 0.05$) for the Drying+Warming than the Control treatment (+2.33°C). Overall, there was no effect ($P > 0.05$) of Intervention Treatment on PWM or WW, and there were no Intervention Treatment by BWC interactions ($P > 0.05$) for these measurements. There was an Intervention Treatment by FPT interaction ($P \leq 0.05$) for PWM. Drying and warming piglets reduced ($P \leq$

0.05) PWM under COOL (by 2.4 percentage units) but not WARM FPT. In addition, WW were lower ($P \leq 0.05$) under WARM than COOL FPT, however, there was no interaction ($P > 0.05$) with Intervention Treatment. In conclusion, this study suggests that drying and warming piglets at birth increases rectal temperature, and may reduce pre-weaning mortality under cooler conditions, which are typical of the majority of the year.

Introduction

Crushing and starvation are the two most common causes of pre-weaning mortality on commercial swine units (PigChamp, 2018). However, hypothermia is often a major pre-disposing factor for both of these causes (Edwards, 2002). At birth, piglets have little body surface insulation, a high body surface to volume ratio, and limited capacity for thermoregulatory heat production, resulting in a high critical temperature (around 35°C; Mount, 1959). In commercial practice, farrowing rooms are typically kept at temperatures between 20 to 22°C on the day of farrowing to prevent heat stress for the sows (Vansickle, 2006). Consequently, piglets are born into a relatively cool environment, resulting in considerable heat loss from the body surface due to convection and radiation. In addition, piglets are born wet and experience heat loss due to evaporation of the amniotic fluid. Therefore, without intervention, all piglets will experience some degree of body temperature decline immediately after birth (Vande Pol et al., 2020a,b,c). This predisposes piglets to mortality, both directly due to hypothermia as a primary cause, and from secondary causes such as starvation, crushing, and disease (Devillers et al., 2011). Low birth weight piglets (i.e., those weighing < 1 kg) are particularly at risk of hypothermia, and have the greatest rates of pre-weaning mortality (Herpin et al., 2002). Reducing the incidence of hypothermia early after birth should, therefore, decrease pre-weaning mortality, particularly in low birth weight piglets.

One common method of limiting piglet heat loss without increasing farrowing room temperature is to include a localized area in the farrowing pen with a higher temperature (e.g. with a heat lamp). However, piglets are generally not confined to this heated area, and are often more attracted to the sow in the early postnatal period (Houbak et al., 2006; Pedersen et al., 2006). Warming boxes (a box placed under the heat source) can be utilized to confine piglets for short periods of time after birth (typically 15 to 30 min) to minimize heat loss. Another method to reduce piglet heat loss is to limit evaporation by drying piglets at birth. Vande Pol et al. (2020b) showed that drying piglets with a desiccant at birth and confining them to a warming box for 30 min after birth were equally effective at reducing early postnatal temperature decline. However, the combination of these two approaches was more effective than either separately. Although both drying and warming of piglets early after birth are used in commercial practice, there has been little published research on the effects of these approaches, individually or in combination, on pre-weaning mortality or weaning weights. The objective of this study was to evaluate the effect of drying and warming newborn piglets on pre-weaning performance.

Materials and Methods

This study was conducted in the farrowing facilities of a commercial breed-to-wean farm of The Maschhoffs, LLC, located near Crawfordsville, IN, during the months of April to November, 2018. The experimental protocol was approved by the University of Illinois Institutional Animal Care and Use Committee prior to the initiation of the research.

Animals, Experimental Design, Treatments, and Allotment

A total of 402 litters (10327 piglets) were used in the study. Sows were from commercial dam lines of Yorkshire and Landrace origin that had been mated to commercial sire lines. The study used a completely randomized design, with litter as the experimental unit and piglet as a subsample of the litter, to compare two Intervention Treatments (applied at birth): Control (no drying or warming); Drying+Warming (piglets were dried at birth by coating with a commercial cellulose-based desiccant until completely dry, then placed in a plastic box under a heat lamp for 30 min; temperature in the box was 36.7 ± 3.12°C). Sows/litters were randomly allotted to an Intervention Treatment at the start of farrowing (after the birth of the first piglet), with the restriction that dam genotype and parity were balanced across treatments.

Housing and Management

Each sow was housed in an individual farrowing crate, located in the center of a farrowing pen, which had either woven metal or perforated plastic flooring. Crate dimensions were 0.55 m by 1.95 m, giving a floor space within the crate of 1.07 m^2; pen dimensions were 1.52 m by 2.07 m, giving a total pen floor space of 3.15 m^2. Crates were equipped with a sow-operated feed dispenser attached to a feed trough, and a nipple-type water drinker for the sow. An infrared heat lamp was suspended in the center of the floor area on one side of the farrowing crate over an insulated rubber mat (average temperature under the heat lamp during the study period was 37.1 ± 3.22°C). For the Drying+Warming treatment, the heat lamp was suspended over a plastic box for the duration of farrowing. Room temperature was maintained using fans and heaters; the thermostat was set at 22.5°C throughout the study period.

Management in the farrowing facility was according to unit protocols, which were generally in line with standard commercial practices. Sows that had not farrowed by d 116 of gestation were induced to farrow on the following d using Lutalyse (1 injection of 1 mL given at 0600 h; Zoetis; Parsippany, NJ); the identity of each sow that was induced and date of induction were recorded. The farrowing process was monitored continuously by the investigators; if the interval between the births of piglets exceeded 60 min, the investigator checked the birth canal for obstructions, and assisted the farrowing process as needed.

Procedures and Measurements

At birth, piglets were given a uniquely numbered ear tag for identification, the allotted Intervention Treatment was applied, and they were returned to the farrowing pen (immediately for the Control and after 30 min in a warming box for the Drying+Warming treatment). Piglets were weighed within 12 h of birth using a Brecknell LPS-15 bench scale (Avery Weigh-Tronix; Fairmont, MN). Scales were calibrated daily prior to use with a standard test weight.

Piglet rectal temperature was measured at 0 and 30 min after birth on a randomly selected sub-sample of 10% of the litters distributed throughout the study period (41 litters and 527 live-born piglets on the Control treatment; 44 litters and 542 live-born piglets on the Drying+Warming treatment). Rectal temperatures were measured on all sows at the start and end of the farrowing process. Piglet and sow rectal temperatures were measured at a depth of 2.5 cm and 10 cm, respectively, using a HSTC-TT-K-24S-36 thermocouple attached via a SMPW-K-M connector to a dual input K/J digital thermometer (HH801A; Omega; Stamford, CT). Thermometers were calibrated each week during the study period by taking measurements in a temperature-controlled chamber that was set at temperatures that encompassed the expected range (i.e., 30, 32, 34, 36, 38, and 40°C). A regression equation for the relationship between measured and set temperatures was developed and was used to adjust rectal temperate measurements taken during the following week of the study.

The temperature in each farrowing pen at three locations [behind and at either side of the sow (one of these measurements being under the heat lamp)] was measured at the beginning and end of the farrowing process using a digital infrared thermometer [TOOGOO GM320 LCD digital infrared thermometer gun (Shenzhen IMC Digital Technology Co. Shenzhen, China)].

Statistical Analysis

The litter of piglets was the experimental unit for all measurements; piglet was a sub-sample of litter. The PROC UNIVARIATE procedure of SAS (SAS Inst. Inc., Cary, NC) was used to verify normality and homogeneity of variances of the residuals. All variables that conformed to the assumptions of normality and homogeneity and were analyzed using the PROC MIXED procedure of SAS (Littell et al., 1996). Mortality data were analyzed using PROC GLIMMIX. The study was carried out using a completely randomized design; the model used for the analysis of sow and litter measurements accounted for the fixed effect of Intervention Treatment. The model used for analysis of Intervention Treatment differences in piglet weight, temperature, and pre-weaning mortality also included the random effect of litter.

An analysis was carried out to determine if the response to Intervention Treatments differed according to piglet birth weight. The dataset was divided into Light (< 1.0 kg), Medium (1.0 to 1.5 kg), or Heavy (> 1.5 kg) Birth Weight Categories (BWC). The maximum weight for the Light category (i.e., 1.0 kg) represented the birth weight below which pre-weaning mortality increases substantially (Zotti et al., 2017). The minimum weight for the Heavy category (i.e., 1.5 kg) represented the weight above which pre-weaning mortality is generally unaffected by birth weight (Zotti et al., 2017).

The study was carried out over a 10 month period that included the summer months when the environmental temperature was relatively high. Consequently, during these periods farrowing room temperatures were also relatively high and above the thermostat set point. This provided an opportunity to investigate the potential effect of ambient temperature in the farrowing pens on piglet responses to drying and warming. The dataset was divided in litters born under COOL (< 25°C) or WARM (≥ 25°C) farrowing pen temperatures (FPT). A temperature of 25°C to divide the dataset was chosen, as some research has suggested that piglet temperatures are higher under warmer conditions (25°C) than when room temperatures are close to the set point (e.g., 20°C; Pedersen et al., 2013).

Piglet rectal temperature, weaning weight, and pre-weaning mortality data were analyzed using a statistical model that included the fixed effects of Intervention Treatment, BWC or FPT, as appropriate, and the interaction, and the random effect of litter. For all analyses, differences between least-squares means were separated using the PDIFF option of SAS, and differences were considered significant at $P \leq 0.05$. All P-values were adjusted using a Tukey's adjustment for multiple comparisons.

Results and Discussion

Sow parameters and farrowing pen temperatures have been summarized by Intervention Treatment in Table 7.1. There were no differences ($P > 0.05$) between Intervention Treatments for any of these except for temperature under the heat lamp before farrowing, which was greater ($P \leq 0.05$) for the Control than the Drying+Warming treatment; however, this difference was relatively small (0.8°C). In general, the pigs used and temperature conditions in the farrowing facilities were typical of U.S. commercial production. The majority of sows on the study were between parities 1 and 8. Average sow temperatures before and after farrowing were between 38.3 and 38.7°C, which is typical for farrowing sows (Littledike et al., 1979). Average farrowing pen temperatures (between 24.4 and 26.4°C; Table 7.1) were higher than the set point (22.5°C). This was as expected; the study was conducted from April through November, which included the summer months, when it was difficult to reduce farrowing room temperatures.

Number of litters and piglets, litter sizes, and piglet birth weights for the entire data set and for the sub-sample of 10% of litters used to measure piglet rectal temperatures are presented in Table 7.2. Number of piglets born alive and birth weights were similar ($P > 0.05$) for the Intervention Treatments for the entire dataset and the sub-sample. In addition, there were no differences between Intervention Treatments ($P > 0.05$) for litter size or birth weight within BWC or FPT for the entire dataset or the sub-sample (Table 7.2). These results suggest that the sub-sample was representative of the entire population. Numbers born alive and birth weights were comparable to those reported for commercial swine populations at the time this study was conducted (PigChamp, 2018; Feldpausch et al., 2019; Vande Pol et al., 2020a,b,c).

Effect of Intervention Treatment

Least-squares means for the effect of Intervention Treatment on piglet rectal temperature at birth and 30 min after birth (from the sub-sample of 10% of litters), weaning weight, and pre-weaning mortality are presented in Table 7.3. Rectal temperatures at birth were similar ($P > 0.05$) for the two Intervention Treatments, which was expected, as treatments were not applied until after birth temperatures were measured. However, temperatures at 30 min after birth were 2.33°C lower ($P \leq 0.05$; Table 7.3) for the Control than the Drying+Warming treatment. Vande Pol et al. (2020b,c), in two studies that utilized the same Intervention Treatments as the current study, also found that temperatures at 30 min after birth were higher for piglets that had been dried and warmed at birth compared to untreated piglets. However, the magnitude of treatment difference was greater in the study of Vande Pol et al. (2020b) than in the study of Vande Pol et al. (2020c; 2.9 and 1.6°C, respectively). The authors suggested that this difference in the magnitude of the response to drying and warming was most likely due differences in farrowing pen temperatures between these two studies (21.8 and 26.6°C, respectively). In support of this concept, farrowing pen temperatures in the current study averaged 25.4°C and the difference between the Intervention Treatments for piglet temperature at 30 min after birth was 2.33°C, which was intermediate to the treatment difference in Vande Pol et al. (2020b,c).

There was no effect ($P > 0.05$) of drying and warming piglets on weaning weight or pre-weaning mortality. This finding was unexpected given the positive effect of the Drying+Warming treatment on piglet temperatures at 30 min after birth. Low body temperature early after birth has been associated with an increased risk of mortality in a number of studies (e.g., Panzardi et al., 2013; Muns et al., 2016; Tuchscherer et al., 2000), however; these studies were based on surveys of piglet survival traits and not on directly controlled experiments. Relatively few studies have directly evaluated the effects of drying and/or warming of piglets at birth on growth or mortality to weaning, and these have produced variable results. Christison et al. (1997) found that pre-weaning mortality was lower for piglets that were either dried or warmed compared to an untreated control, however, there was no effect on piglet weaning weight. Andersen et al. (2009) found that piglets that were dried and/or placed under a heat lamp at birth had reduced mortality compared to untreated piglets; weaning weights were not reported. In contrast, and in agreement with the results of the current study, a number of studies report that drying or warming piglets at birth had no effect on pre-weaning growth or mortality (McGinnis et al., 1981; Ogunbameru et al., 1991; Vasdal et al., 2011). Other studies have included drying or warming in multi-factorial treatments in combination with many other interventions, making it impossible to determine which factors caused any treatment effects (White et al., 1996; Dewey et al., 2008).

Interaction with Farrowing Pen Temperature

Least-squares means for the effect of FPT and the interactions with Intervention Treatment for piglet rectal temperatures, weaning weight, and pre-weaning mortality are presented in Table 7.4. Piglet temperatures at birth were greater ($P \leq 0.05$) under WARM than COOL FPT; however, this difference was relatively small (< 0.2°C). The body temperature of sows during farrowing has been shown to be higher under warmer than under cooler conditions (Muns et al., 2016), which may be the cause of the difference in piglet birth temperature observed in the current study. There was an interaction ($P \leq 0.05$) between FPT and Intervention Treatment for piglet temperature at 30 min after birth (Table 7.4). Temperatures for the Control were greater ($P \leq 0.05$) under WARM than COOL FPT, whereas, in contrast, temperatures for the Drying+Warming treatment were similar ($P > 0.05$) for the two FPT. Therefore, while drying and warming of piglets resulted in higher temperatures than the Control at both FPT, the difference between the Intervention Treatments was greater under COOL than WARM conditions (Table 7.4). In agreement, Vande Pol et al. (2020c) also showed that drying and warming piglets at birth resulted in a greater increase in temperatures in the early postnatal period relative to untreated piglets, and suggested that, while this intervention was effective across the range of temperatures typically experienced in commercial production, it was more effective under cooler conditions.

Piglet weaning weight was greater ($P \leq 0.05$) under COOL than WARM FPT, however, there was no interaction ($P > 0.05$) with Intervention Treatment. Higher temperatures during lactation can reduce sow milk yield (Black et al., 1993), which could potentially explain these effects of FPT on piglet weaning weight. There was an Intervention Treatment by FPT interaction ($P \leq 0.05$) for PWM. The Drying+Warming treatment reduced ($P \leq 0.05$) pre-weaning mortality compared to the Control under COOL but not WARM FPT (Table 7.4). Farrowing pen temperatures were measured for each litter on the day of farrowing only and, therefore, are indicative of temperatures in the facilities for that day. The thermostat in each of the farrowing rooms used in this study was set at 22.5°C for the day of farrowing and was reduced to 18°C on the following day, where it was maintained to weaning. However, the farrowing days with the higher pen temperatures corresponded to the summer months when cooling to the set point was not achieved. In addition, allotments to the study were carried out on most days during the summer period, when measured farrowing pen temperatures were consistently above 25°C, which was the cut off temperature for the two FPT treatments. On this basis, it is likely that the temperatures on the day of farrowing were representative of the conditions experienced throughout lactation.

There has been limited research on the effect of ambient temperatures during lactation on piglet weaning weights. Similar to the results of the current study, Stansbury et al. (1987) found that litter weaning weights were greater at lower (18 or 25°C) compared higher (30°C) farrowing room temperatures. Pedersen et al. (2015) found that low birth weight piglets (10^{th} percentile) in the litter had lower weaning weights at room temperatures of 15°C, whereas the heavy piglets (90^{th} percentile) were lighter at weaning at room temperatures of 25°C. In the current study, there was no interaction ($P > 0.05$) between FPT and BWC (data not reported), indicating that higher farrowing pen temperatures reduced weaning weights to a similar extent for piglets of all BWC.

In the current study, the finding that drying and warming of piglets reduced mortality under cooler but not warmer temperatures is interesting but requires validation. The results of Vande Pol et al. (2020a,b) and of the current study were consistent in demonstrating that drying and warming of piglets at birth was more effective at reducing the extent and duration of postnatal temperature decline under cooler than warmer conditions. Collectively, these results suggest that hypothermia is an important cause of pre-weaning mortality, either directly or indirectly, under temperature conditions that prevail in farrowing facilities for major period of the year, certainly in temperate climates. The only study to report on the effects of farrowing room temperature on pre-weaning mortality was that of Stansbury et al. (1987). That study found that the lowest mortality was in rooms kept at an intermediate temperature (25°C) compared those at lower or higher temperatures (18 and 30°C, respectively). However, no piglet intervention treatments were applied in the study of Stansbury et al. (1987). There is an obvious need for further research, ideally designed to directly compare room temperature treatments, to clarify the relationships between ambient temperature and piglet intervention treatments.

Interaction with Birth Weight Category

Results for the effect of piglet BWC and interactions with Intervention Treatment on piglet rectal temperatures, weaning weight, and pre-weaning mortality are presented in Table 7.5. Piglet temperatures at birth differed ($P \leq 0.05$) between BWC; however, differences were small (< 0.2°C). There was an interaction ($P \leq 0.05$) between Intervention Treatment and BWC for piglet temperature at 30 min (Table 7.5). Light piglets had lower ($P \leq 0.05$) temperatures than the other two BWC for both Intervention Treatments, however, this difference was greater for the Control than the Drying+Warming treatment. For example, the difference in temperature between Light and Heavy BWC was 2.49°C and 0.88°C for the Control and Drying+Warming treatments, respectively. In addition, the Drying+Warming treatment resulted in greater ($P \leq 0.05$) temperatures than the Control for all BWC, but the difference between the two treatments was greater for Light than Medium or Heavy piglets (3.49, 2.54, and 1.88°C higher, respectively;

Table 7.5). These results highlight that lighter birth weight piglets are more pre-disposed to hypothermia in the early postnatal period than heavier littermates, which is in agreement with the findings of a number of studies (Pattison et al.,1990; Pedersen et al., 2016; Cooper et al., 2019; Vande Pol et al., 2020a,b,c). The results of the current study also suggest that drying and warming of piglets at birth was more effective at reducing the extent of postnatal temperature decline in lower birth weight piglets than for heavier littermates. This is similar to the studies of Vande Pol et al. (2020b,c), which also showed that the magnitude of the temperature difference between the Drying+Warming and Control treatments at 30 min after birth decreased with increasing birth weight.

Light piglets had lower ($P \leq 0.05$) weaning weights and higher ($P \leq 0.05$) pre-weaning mortality than Heavy piglets; Medium piglets were intermediate and different ($P \leq 0.05$) to the other BWC for both measures (Table 7.5). A number of other studies have reported a negative relationship between birth weight and weaning weight and pre-weaning mortality (Charal, 2009; Panzardi et al., 2013). In addition, Quiniou et al. (2002) found that weaning weight had a strong positive correlation with birth weight (r = 0.57). These results highlight that piglet birth weight is a major factor influencing both weaning weight and pre-weaning mortality.

Despite the considerable effect of birth weight on pre-weaning mortality, there was no effect ($P > 0.05$) of the Drying+Warming treatment on this measurement within any BWC. This result was unexpected given that this Intervention Treatment reduced postnatal temperature decline to a greater extent for lower birth weight piglets than their heavier littermates (Table 7.5). Only one other study has evaluated the effect of drying or warming on pre-weaning mortality for piglets of differing birth weights. In agreement with the results of the current study, Christison et al. (1997), in a small-scale study, found no effect of either drying or placing piglets under a heat lamp compared to an untreated control on pre-weaning mortality of low birth weight piglets ($<$ 1.05 kg).

A number of studies have carried out retrospective multi-variate analyses of commercial datasets, and have found that low birth weight is a major predisposing factor for pre-weaning mortality (Charal, 2009; Pedersen et al., 2011; Muns et al., 2016). In addition, many other studies have reported that low rectal temperature in the early postnatal period is a significant predictor of pre-weaning mortality (Tuchscherer et al., 2000; Rothe, 2011; Pedersen et al., 2011; Muns et al., 2016). However, the time of temperature measurement after birth that was the best predictor of mortality varied greatly across studies (e.g., 1 h after birth for Tuchscherer et al., 2000 vs 72 h after birth for Muns et al., 2016). In addition, Panzardi et al. (2013) found that, of many factors evaluated, the odds ratio for pre-weaning mortality increased with decreasing birth weight and decreasing rectal temperature at 24 h after birth, however, birth weight explained the most variation. It needs to be emphasized that all of these studies were based on population surveys carried out on commercial facilities rather than from a direct comparison of specific treatments.

Regressions

The regression relationships between piglet temperatures at 30 min after birth and birth weight for each Intervention Treatment are illustrated in Figure 7.1. There was a significant ($P \leq 0.05$) quadratic relationship between the two variables for both treatments, however, the relationships were substantially different between treatments. Predicted temperatures were lower for the Control than for the Drying+Warming treatment for piglets of all birth weights (Figure 7.1), and the change in predicted temperature with increasing birth weight was greater for the Control than the Drying+Warming treatment. This is illustrated by calculating the predicted temperature difference between the lightest and heaviest birth weight piglets (i.e., 0.5 and 3.0 kg, respectively) for the two treatments, which was relatively small for the Drying+Warming (0.2°C) compared to the Control (2.5°C) treatment (Figure 7.1).

A number of other studies (Vande Pol et al., 2020a,b,c) have used identical Intervention Treatments to those of the current study, and the quadratic relationship between piglet temperatures at 30 min after birth and birth weight for the Control and Drying+Warming treatments have been estimated for each study (using individual piglet data) and these are reported in Table 7.6. Within each Intervention Treatment, regression coefficients were generally similar across all studies, indicating that the effect of piglet birth weight on temperatures was relatively consistent, within treatment. In all of these studies, the intercepts were lower ($P \leq 0.05$), and the linear and quadratic coefficients were greater ($P \leq 0.05$) for the Control than the Drying+Warming treatments. This suggests that treatment effects were relatively consistent across studies. These relationships indicate that, as previously discussed, drying and warming generally reduced the effect of birth weight on piglet temperature, resulting in lighter birth weight piglets having temperatures more similar to their heavier littermates.

In the current study, the relative importance of birth weight and postnatal temperature in determining the probability of pre-weaning mortality was evaluated using logistic regression analyses of the dataset for the sub-sample of piglets that had rectal temperature measurements, and the results of this analysis are presented in Table 7.7. Three different statistical models were used: Model 1 included birth weight, Model 2 included rectal temperature (at 30 min after birth), and Model 3 included both factors. Linear and quadratic terms for these factors were included in all of the models. Piglet birth weight and rectal temperature at 30 min after birth were individually significant predictors for the probability of pre-weaning mortality (Models 1 and 2, respectively; Table 7.7). However, birth weight was the only significant ($P \leq 0.05$) predictor when both terms were included (Model 3). This suggests that piglet birth weight was the most important factor for predicting pre-weaning mortality, and that piglet temperature at 30 min after birth was relatively unimportant in comparison. This is in agreement with the findings of Panzardi et al. (2013).

In conclusion, the results of this study found effects of drying and warming on piglet temperatures at 30 min after birth that were consistent with those of previous research. As expected, piglets of lower birth weight had lower weaning weights and greater pre-weaning mortality than heavier littermates. However, there were no effects of drying and warming on weaning weight or pre-weaning mortality for either the entire population, or within any of the birth weight categories. Drying and warming piglets reduced pre-weaning mortality under cooler but not warmer conditions, and for both Intervention Treatments, piglets had greater weaning weights under cooler conditions. It is clear that the factors influencing pre-weaning mortality levels are complex, and there is a need for more large-scale controlled research studies to fully understand the potential interventions that may reduce these.

Tables and Figure

Table 7.1. Summary of sow parity and rectal temperature and ambient temperatures in the farrowing pen during the study by Intervention Treatment.

	Intervention Treatment[1]			
Item.	Control	Drying+ Warming	SEM	*P*-value
Number of litters	400	402	-	-
Average sow parity[2]	4.1	4.1	0.14	0.96
Number of sows by parity[2]				
Parity 1	58	60	-	-
Parity 2	29	27	-	-
Parity 3 and 4	74	74	-	-
Parity 5 to 8	199	198	-	-
Parity 9+	40	43	-	-
Sow rectal temperature, °C				
Start of farrowing	38.3	38.3	0.04	0.32
After farrowing	38.7	38.7	0.03	0.26
Farrowing pen temperature, °C				
Before Farrowing				
Under heat lamp	37.1[a]	36.3[b]	0.15	0.0002
Side of pen opposite heat lamp	24.7	24.8	0.12	0.70
Behind sow	24.4	24.5	0.12	0.91
After Farrowing				
Under heat lamp	37.2	37.5	0.16	0.18
Side of pen opposite heat lamp	26.1	26.4	0.14	0.20
Behind sow	25.6	25.7	0.14	0.58

[a,b]Within a row, means with differing superscripts differ at $P \leq 0.05$.

[1]Control = piglets were not dried; Drying+Warming = piglets were dried at birth by coating with a desiccant, then placed in a warming box for 30 min.

[2]Parity = total number of litters including the one used in the study.

Table 7.2. Effect of Intervention Treatment on litter size and piglet birth weight, within farrowing pen temperature (FPT) and birth weight category (BWC) for the entire data set and the sub-sample of 10% of litters used to measure piglet rectal temperatures.

	Entire data set				Sub-sample			
	Intervention Treatment[1]				Intervention Treatment[1]			
Item.	Control	Drying+ Warming	SEM	*P*-value	Control	Drying+ Warming	SEM	*P*-value
Number of litters	400	402	-	-	41	44	-	-
Number of piglets born alive	5164	5163	-	-	527	542	-	-
By FPT[2]								
COOL	1891	1828	-	-	173	168	-	-
WARM	3273	3335	-	-	354	374	-	-
By BWC[3]								
Light	628	669	-	-	56	84	-	-
Medium	2187	2139	-	-	228	224	-	-
Heavy	2349	2355	-	-	243	234	-	-
Litter size, born alive								
Overall	12.9	12.7	0.19	0.55	13.4	12.2	0.57	0.13
By FPT[2]								
COOL	12.7	12.0	0.21	0.08	13.9	11.3	0.66	0.06
WARM	13.0	13.4	0.17	0.22	13.0	13.0	0.49	0.97
Piglet birth weight, kg								
Overall	1.49	1.48	0.013	0.67	1.49	1.43	0.042	0.34
By FPT[2]								
COOL	1.48	1.49	0.014	0.64	1.42	1.40	0.035	0.79
WARM	1.51	1.47	0.011	0.09	1.55	1.46	0.049	0.21
By BWC[3]								
Light	0.86	0.86	0.006	0.95	0.82	0.85	0.019	0.37
Medium	1.31	1.32	0.005	0.68	1.30	1.31	0.013	0.70
Heavy	1.78	1.77	0.004	0.17	1.79	1.74	0.013	0.06

[a,b]Within a row, means with differing superscripts differ at $P \leq 0.05$.

[1]Control = piglets were not dried; Drying+Warming = piglets were dried at birth by coating with a desiccant, then placed in a warming box for 30 min.

[2]COOL = < 25°C; WARM = ≥ 25°C.

[3]Light = < 1.0 kg; Medium = 1.0 to 1.5 kg; Heavy = > 1.5 kg.

Table 7.3. Least-squares means for the effect of Intervention Treatment (IT) on piglet rectal temperature at birth and 30 min after birth (from the sub-sample of 10% of litters), weaning weight, and pre-weaning mortality.

Item.	IT[1] Control	IT[1] Drying+ Warming	SEM	*P*-value
Piglet rectal temperature at birth, °C	38.72	38.65	0.051	0.38
Piglet rectal temperature at 30 min after	35.65[b]	37.98[a]	0.095	<0.0001
Weaning weight, kg	5.35	5.23	0.053	0.07
Pre-weaning mortality, %	16.4	15.7	-	0.32

[a,b]Within a row, means with differing superscripts differ at $P \leq 0.05$.

[1]Control = piglets were not dried; Drying+Warming = piglets were dried at birth by coating with a desiccant, then placed in a warming box for 30 min.

Table 7.4. Least-squares means for the effect of farrowing pen temperature (FPT) on piglet rectal temperature at birth and 30 min after birth (from the sub-sample of 10% of litters), weaning weight, and pre-weaning mortality.

Item.	Main effect of FPT[1]	SEM	P-value	IT[2]		IT x FPT interaction	
				Control	Drying+ Warming	SEM	P-value
Piglet rectal temperature at birth, °C		0.052	0.03			0.053	0.25
COOL	38.57^{b}	-	-	-	-	-	-
WARM	38.74^{a}	-	-	-	-	-	-
Piglet rectal temperature at 30 min after birth, °C		0.094	0.01			0.094	0.03
COOL	36.63^{b}	-	-	35.32^{c}	37.94^{a}	-	-
WARM	37.00^{a}	-	-	35.98^{b}	38.03^{a}	-	-
Weaning weight, kg		0.052	<0.0001			0.052	0.25
COOL	5.77^{a}	-	-	-	-	-	-
WARM	4.98^{b}	-	-	-	-	-	-
Pre-weaning mortality, %		-	0.93			-	0.05
COOL	16.0	-	-	17.2^{a}	14.8^{b}	-	-
WARM	16.0	-	-	15.9^{ab}	16.2^{ab}	-	-

[a,b,c]Within a column (main effects), or interaction (if significant), means with differing superscripts differ at $P \leq 0.05$.

[1]COOL = < 25°C; WARM = ≥ 25°C.

[2]Control = piglets were not dried; Drying+Warming = piglets were dried at birth by coating with a desiccant, then placed in a warming box for 30 min.

Table 7.5. Least-squares means for the effect of birth weight category (BWC) on piglet rectal temperature at birth and 30 min after birth (from the sub-sample of 10% of litters), weaning weight, and pre-weaning mortality.

Item.	Main effect of BWC[1]	SEM	*P*-value	IT[2]		IT x BWC interaction	
				Control	Drying+ Warming	SEM	*P*-value
Piglet rectal temperature at birth, °C		0.04	<0.0001			0.056	0.24
Light	38.56[c]	-	-	-	-	-	-
Medium	38.67[b]	-	-	-	-	-	-
Heavy	38.73[a]	-	-	-	-	-	-
Piglet rectal temperature at 30 min after birth, °C		0.072	<0.0001			0.102	<0.0001
Light	35.58[c]	-	-	33.83[e]	37.32[b]	-	-
Medium	36.75[b]	-	-	35.48[d]	38.02[a]	-	-
Heavy	37.26[a]	-	-	36.32[c]	38.20[a]	-	-
Weaning weight, kg		0.048	<0.0001			0.042	0.25
Light	3.73[c]	-	-	-	-	-	-
Medium	4.84[b]	-	-	-	-	-	-
Heavy	5.86[a]	-	-	-	-	-	-
Pre-weaning mortality, %		-	<0.0001			-	0.95
Light	44.6[a]	-	-	-	-	-	-
Medium	15.9[b]	-	-	-	-	-	-
Heavy	8.2[c]	-	-	-	-	-	-

[a,b,c,d,e]Within a column (main effects) or interaction (if significant), means with differing superscripts differ at $P \leq 0.05$.
[1]Light = < 1.0 kg; Medium = 1.0 to 1.5 kg; Heavy = > 1.5 kg.
[2]Control = piglets were not dried; Drying+Warming = piglets were dried at birth by coating with a desiccant, then placed in a warming box for 30 min.

Table 7.6. Regression coefficients for the linear and quadratic effects of birth weight (BW) on piglet rectal temperature at 30 min after birth.

	Control[1]			Drying+Warming[2]		
Study.	Intercept	BW	BW^2	Intercept	BW	BW^2
Current	30.1	6.1	-1.4	34.9	3.8	-1.0
Vande Pol et al., 2020a	29.8	6.0	-1.3	-	-	-
Vande Pol et al., 2020b	30.2	4.9	-1.0	33.4	3.5	-0.6
Vande Pol et al., 2020c	30.0	7.5	-1.9	35.7	3.0	-0.8

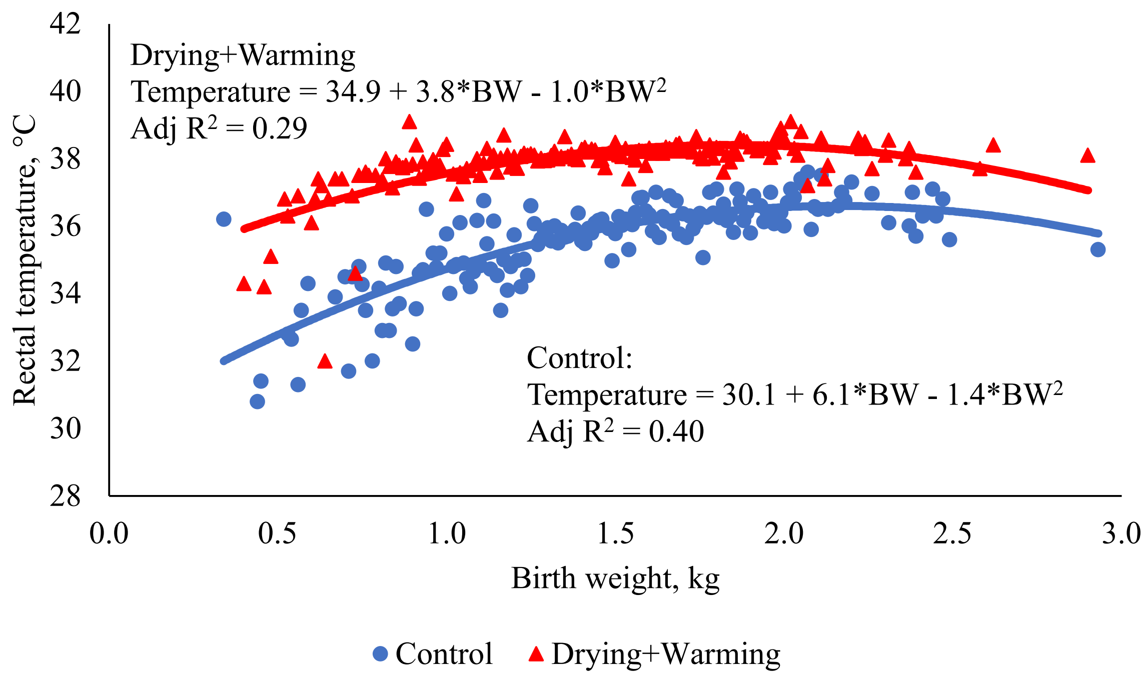
[1]Control = piglets were not dried or warmed.

[2]Drying+Warming = piglets were dried at birth by coating with a desiccant, then placed in a warming box for 30 min.

Table 7.7. Regression coefficients for the effects of birth weight (BW) and piglet rectal temperature at 30 min after birth on piglet pre-weaning mortality.

Model#	Item.	Intercept	BW	BW^2	30 min Rectal Temperature	30 min Rectal Temperature^2
1						
	Coefficient	3.94	-6.35	1.51	-	-
	SE	0.26	0.392	0.141	-	-
	P-value	<0.0001	<0.0001	<0.0001	-	-
2						
	Coefficient	83.87	-	-	-4.38	0.06
	SE	37.013	-	-	2.051	0.028
	P-value	0.02	-	-	0.03	0.05
3						
	Coefficient	22.25	-4.3	0.75	-0.88	0.01
	SE	35.265	1.394	0.517	1.964	0.027
	P-value	0.53	0.002	0.15	0.65	0.73

Figure 7.1. Regression for the effect of birth weight on piglet rectal temperature at 30 min after birth, by Intervention Treatment.



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CHAPTER 8: Effect of rearing cross-fostered piglets in litters of either uniform or mixed birth weights on pre-weaning growth and mortality

Abstract

Cross-fostering is a common practice used in the commercial swine industry to equalize litter sizes, however, there is limited understanding of the optimum cross-fostering method to maximize piglet performance. This study evaluated the effects of within-litter variation in birth weight after cross-fostering on piglet pre-weaning mortality (PWM) and weaning weight in litters of 15 piglets. A hierarchical incomplete block design was used (blocking factors day of farrowing and sow parity, body condition score, and number of functional teats) with a 3 by 2 factorial arrangement of treatments: 1) Birth Weight Category (BWC): Light (< 1.0 kg), Medium (1.0 to 1.5 kg), or Heavy (1.5 to 2.0 kg); 2) Litter Composition (LC): Uniform (all piglets in the litter of the same BWC), or Mixed (equal numbers of piglets in the litter from each BWC). Piglets were weighed at 24 h after birth and randomly allotted to LC treatments. The experimental unit was five piglets of the same BWC, with three experimental units within each LC litter. There were 17 blocks of six litters (one Uniform litter of each BWC; three Mixed litters) for a total of 102 cross-fostered litters and 51 replicates (three replicates/block of six litters). Piglets were weaned at 19.7 ± 0.46 d of age; weaning weights and PWM were measured. PROC GLIMMIX and MIXED of SAS were used to analyze PWM and all other data, respectively. Models included BWC, LC, the interaction, and replicate within block. There were treatment interactions ($P \leq 0.05$) for PWM and weaning weight. There was no effect ($P > 0.05$) of LC on weaning weight for Light or Medium piglets; Heavy piglets had greater ($P \leq 0.05$) weaning weights in Mixed than in Uniform litters. Pre-weaning mortality was greater ($P \leq 0.05$) for Light piglets in Mixed than in Uniform litters. In contrast, PWM for Heavy piglets was

greater ($P \leq 0.05$) in Uniform than in Mixed litters. Pre-weaning mortality of Medium piglets was similar ($P > 0.05$) across LC treatments. The results of this study, which involved litter sizes typical of current commercial production, suggested that cross-fostering to create litters of Uniform birth weights reduced PWM of Light piglets, but increased PWM and reduced weaning weights of Heavy piglets, with no effect on either PWM or weaning weight for Medium piglets.

Introduction

Pre-weaning mortality levels on commercial sow farms have increased over recent years and currently average around 12 to 15% of piglets born alive (PigChamp, 2004, 2019; SEGES, 2017; Agriculture and Horticulture Development Board, 2020). This represents a major economic loss to producers and is also a significant welfare concern. This increase in pre-weaning mortality has been associated with the increases in litter sizes that have occurred over the same time period (PigChamp, 2004, 2019). Currently, in commercial production, total number born typically averages between 15 and 17 piglets per litter (SEGES, 2017; PigChamp, 2019). Larger litters have lower average piglet birth weights and an increased number of low birth weight piglets. Estimates suggest that 10 to 15% of piglets born are of low birth weight (i.e., weighing < 1 kg) and that mortality levels for these piglets are extremely high (Herpin et al., 2002). In addition, it is increasingly common for the number of piglets born alive within a litter to exceed the number of functional teats of the sow. As a consequence, developing practical approaches to rearing this greater number of piglets is of increasing importance.

Cross-fostering of piglets has been widely used in practice to equalize litter sizes and/or match the number of piglets within a litter to the number of functional teats on the sow. In practice, there are many potential approaches to cross-fostering, with major factors for consideration including piglet birth weight, the proportion of the litter to be cross-fostered, the optimum litter size, and within-litter weight variation after cross-fostering. Unfortunately, published research in this area is extremely deficient. Most published studies have evaluated a limited number of the major factors that can contribute to a practical cross-fostering protocol. Some studies have focused on light birth weight piglets, to the exclusion of heavier piglets, making results of limited application (e.g. English and Bilkei, 2004; Deen and Bilkei, 2004; Douglas et al., 2014). In theory, these light piglets should be better able to compete for teat access when they are reared with piglets of similar weight. However, this approach would also result in rearing heavier birth weight piglets in litters of reduced weight variation, and it is not clear how this would affect piglet competition within the litter and, ultimately, pre-weaning performance of the entire population of piglets.

In addition, many studies that evaluated the effect of within-litter weight variation have been carried out on university research facilities and have had insufficient replication to detect practically important differences in pre-weaning mortality levels (e.g. Milligan et al., 2001; Huting et al., 2017). Other studies have involved retrospective analyses of historical sow production records; by definition such approaches result in no control over study conditions, and, in addition, often lack a clear definition of the cross-fostering protocols and procedures that were utilized (e.g. Zindove, 2011; Roehe and Kalm, 2000). Perhaps most importantly, there has been little if any research on cross-fostering carried out with the large litter sizes that are typical of current commercial conditions. Given this variation in study design and execution, it is not surprising that the historical cross-fostering literature is often contradictory. Therefore, there is a need for a comprehensive research-based evaluation of the various components of cross-fostering to provide objective data for the development of optimum protocols to maximize piglet pre-weaning performance. The objective of the current study was to evaluate the effect of rearing cross-fostered piglets in litters of either uniform or mixed birth weight on piglet pre-weaning performance under commercial conditions, using litter sizes that are typical of current commercial production.

Materials and Methods

This study was carried out on a commercial sow facility of The Maschhoffs, LLC, located near Beardstown, IL, USA. Protocols for this study were approved by the University of Illinois Institute of Animal Care and Use Committee prior to the start of the research.

Experimental Design and Treatments

This study utilized a hierarchical incomplete block design with a 3 by 2 factorial arrangement of the following treatments: Birth Weight Category (BWC): Light = 0.50 to 1.04 kg; Medium = 1.05 to 1.50 kg; Heavy = 1.51 to 2.00 kg; Litter composition (LC): Uniform = all piglets in the litter from either the Light, Medium, or Heavy BWC; Mixed = equal numbers of piglets in the litter from the Light, Medium, and Heavy BWC. Piglets weighing < 0.50 kg or > 2.00 kg were not used in the study. The maximum weight for the Light category (i.e., 1.0 kg) represented the birth weight below which pre-weaning mortality increases substantially (Zotti et al., 2017). The minimum weight for the Heavy category (i.e., 1.5 kg) represented the weight above which pre-weaning mortality is generally unaffected by birth weight (Zotti et al., 2017). All litters had 15 piglets after cross-fostering, and every piglet was cross-fostered.

Animals and Management

The sows used were from standard commercial crossbred lines, mated to commercial sire lines. Housing and management of sows and piglets were generally in line with commercial procedures and practices. Sows were moved into the farrowing rooms around 112 d of gestation. All sows within an allotment group had been inseminated on the same day and were induced on d 114 to farrow on d 115 of gestation using 2 cc of prostaglandin F2α (given at 0600 h; Lutalyse®, Pfizer Animal Health US). The facilities used consisted of rooms with 48 individual farrowing crates and pens. Farrowing pens were 1.52 m x 2.07 m (total pen floor space of 3.15 m^2), with solid side walls and woven metal flooring. A farrowing crate was located in the center of each pen and was 0.55 m x 1.95 m (floor space within the crate of 1.07 m^2). The thermostat in the farrowing rooms was set at 22.4°C on the day of farrowing and subsequently at 18.0°C. Room temperature was maintained using heaters, evaporative coolers, and fan ventilation as needed.

During gestation and lactation, sows were fed diets formulated to meet or exceed the nutritional requirements proposed by the National Research Council (2012). From entry into the farrowing facility until the start of farrowing, sows were fed approximately 1 kg of feed twice each day (at approximately 0600 h and 1400 h). Subsequently, sows had *ad libitum* access to feed throughout lactation via a sow-operated feed dispenser attached to the feed trough. Sows and piglets had *ad libitum* access to water via nipple-type drinkers located in the sow feeding trough and farrowing pen, respectively. Standard pig processing tasks (tail docking, castration of males, iron and antibiotic injections) were carried out at approximately five days after birth. Sows and litters were taken off-test when piglets reached 19 or 20 d of age, depending on farrowing date, and piglets were weaned from the sow at 21 d of age.

Pre-allotment Data Collection

Sow parity, genetic line, body condition score (on a scale of 1 = extremely thin to 5 = extremely fat) and number of teats within each functionality score [Score 1 = ideal (teat elongated with no visible defects); Score 2 = not ideal (teat functional, not as elongated, but with no visible defects); Score 3 = non-functional (teat severely damaged or visibly defective)] were determined on all sows two days prior to allotment. On the day after farrowing, piglet gender and individual weight were recorded, and each piglet was given a uniquely numbered ear tag. Piglets that were considered by the investigators to be non-viable were weighed and recorded, but not used in the study.

Allotment Process

The allotment process was carried out on the day after farrowing in two stages; firstly, piglets were allotted to treatments to form litters of 15, and secondly, sows were allotted to litters. Litters within a block were formed to have no more than three littermates within a litter, equal numbers of piglets of each gender (± 1), and similar mean birth weights within BWC and gender (± 0.05 kg). This was accomplished using outcome groups of six piglets of the same BWC and gender; piglets were randomly allotted to treatments from within each outcome group. Piglets were moved between litters as necessary to ensure that all piglets were cross-fostered and litters met the allotment restrictions above. After the piglets were allotted, six sows were selected with similar parities (± 1; no parity one gilts were used), similar body condition score (± 1), and a similar number of functional teats (± 1) and randomly allotted to these litters. Sow genetic line was balanced across LC treatments within the study.

Measurements

Piglets were weighed again at the end of the test period (weaning weight), and average daily gain was calculated. Litters were checked daily and all piglets were given a vitality score (on a scale of 1 to 4): Score 1 = Emaciated and piglet showed signs of weakness and lethargy; Score 2 = Very thin and piglet showed some signs of lethargy, but still able to nurse; Score 3 = Thin but piglet had high energy levels and normal behavior; Score 4 = Ideal, with piglet having adequate body condition, high energy levels, and normal behavior. Piglets with a vitality score 1 were euthanized; those with a score of 2 were removed from the litter and placed on a non-test sow with small piglets; those with a score of 3 were treated according to farm protocol but remained on-test; those with a score 4 were not treated and remained on-test. Piglets removed from the study due to a vitality score of 1 or 2 were classified as a mortality, and the date, tag number, vitality score, weight, and cause of mortality were recorded. Necropsies were performed on all piglets that died during the study period to determine cause of death and to measure full and empty stomach weights to calculate the weight of stomach contents.

Quality Assurance

Weigh scales used for measurement of piglet birth and weaning weights were validated prior to each collection of weights using standard check weights that approximated to the average expected piglet birth and weaning weight (i.e. 1.00 and 5.00 kg at birth and weaning, respectively). Necropsies were carried out by the principal investigator, who was fully trained and experienced in proper necropsy procedure to ascertain the cause of piglet death. The number of live and dead pigs were recorded each day and reconciled with the previous daily record of piglet numbers to ensure the validity of all mortality data.

Statistical Analysis

All data were analyzed using SAS v. 9.4 (SAS Inst. Inc., Cary, NC). This study utilized a hierarchical incomplete block design with a 3 by 2 factorial arrangement of BWC and LC treatments. There were 51 replicates and 17 blocks, for a total of 102 sows/litters and 1,530 piglets used in the study. Blocks consisted of six sows/litters, with one litter of each Uniform birth weight, and three Mixed birth weight litters to equalize the number of piglets within each LC and BWC combination. A replicate consisted of 30 piglets, in six groups of five piglets: two groups from each BWC (Light, Medium, or Heavy), each group being in one of the LC treatments (Uniform or Mixed); there were three replicates per block.

The PROC UNIVARIATE procedure of SAS was used to verify normality and homogeneity of variances of the residuals. All variables that conformed to the assumptions of normality and homogeneity (directly or through transformation of the data) were analyzed using the PROC MIXED procedure of SAS (Littell et al., 1996). Pre-weaning mortality data were analyzed using PROC GLIMMIX. The model to analyze piglet weight data accounted for the fixed effects of LC, BWC, and the interaction, and the random effects of replicate within block. Pre-weaning mortality data were analyzed using individual piglet data as a binary response; the model included the fixed effects of LC, BWC, and the interaction. Least-squares means for the effects of LC and BWC were separated using the PDIFF option of SAS, being considered different at $P \leq 0.05$.

Results and Discussion

Sow Parameters

A summary of sow parameters for the LC treatments is presented in Table 8.1. There were no differences ($P > 0.05$) between LC for sow parity, body condition score, or number of teats. All sows were between parity 2 and 7, with averages of 4.2 and 4.3 for the Uniform and Mixed treatments, respectively. Body condition scores were between 2.0 and 4.5, and averages were 3.4 and 3.6 for the Uniform and Mixed treatments, respectively. The average number of functional teats (scores 1 and 2) was 14.4 for both LC treatments, with the number of non-functional teats (Score 3) being 0.4 and 0.2 for the Uniform and Mixed treatments, respectively (Table 8.1).

In general, the sows used in this study were typical of those found in commercial production. Maes et al. (2004) surveyed three commercial sow herds and reported an average body condition score at farrowing of 3.2, using the same five-point scale as in the present study. Similarly, Esbenshade et al. (1986) reported that sows of Landrace and Yorkshire dam lines generally had similar body condition scores across parities, and averaged around 5.7 on a scale of 1 to 9, with a score of 1 being extremely thin and 9 being extremely fat. Kim et al. (2005) reported that the average number of teats for Duroc, Landrace, and Yorkshire gilts were 12.5, 14.9, and 13.7, respectively, which is similar to the numbers found in the current study. Balzani et al. (2016) subjectively evaluated teat functionality in a population of cross-bred sows, with parities ranging from 1 to > 6; 82% of teats were scored as perfectly functional, with 16% partially functional, and 0.2% completely non-functional. These results are similar to the teat functionality scores of the current study, of 78.5, 21.5, and 2.8% with a score of 1, 2, and 3, respectively.

Piglet Weights and Pre-weaning Mortality

Least-squares means for the effect of LC and BWC on piglet birth weight, weaning weight, pre-weaning average daily gain (ADG), and pre-weaning mortality (PWM) are presented in Table 8.2. There was no effect of LC or interaction between LC and BWC ($P > 0.05$) for piglet birth weights. By design, birth weights differed ($P \leq 0.05$) between BWC, with Heavy piglets having the greatest ($P \leq 0.05$) weights, Light piglets having the lowest ($P \leq 0.05$), and Medium piglets being intermediate ($P \leq 0.05$) to the other two categories (Table 8.2). There were LC by BWC interactions ($P \leq 0.05$) for weaning weight and pre-weaning ADG (Table 8.2). There was no effect of LC ($P > 0.05$) on the weaning weights of Light or Medium piglets, however, weaning weights of Heavy piglets were greater ($P \leq 0.05$) in Mixed than Uniform litters (Table 8.2).

Pre-weaning ADG of weaned piglets (not including all piglets removed prior to weaning for PWM) followed a similar pattern to weaning weights, with no effect ($P > 0.05$) of LC for Light or Medium piglets (Table 8.2). However, ADG of weaned Heavy piglets was greater ($P \leq 0.05$) in Mixed than Uniform litters. Similarly, pre-weaning ADG of all piglets (including those removed for PWM) was greater ($P \leq 0.05$) for Heavy piglets in Mixed than Uniform litters, with no effect ($P > 0.05$) of LC for Medium piglets. However, Light piglets had greater ($P \leq 0.05$) ADG in Uniform than Mixed litters. For PWM, there was no effect ($P > 0.05$) of LC for Medium piglets. However, PWM was greater ($P \leq 0.05$) for Light piglets in Mixed than in Uniform litters, whereas the opposite was the case for Heavy piglets, which had greater PWM ($P \leq 0.05$) in Uniform than Mixed litters (Table 8.2).

A number of previous studies that evaluated the effect of within-litter variation in piglet weights at birth (either with or without cross-fostering) found that increased variation generally reduced piglet performance. Two studies reported on retrospective analyses of sow and piglet performance, without using specific cross-fostering treatments. Zindove (2011) analyzed 12 years of data from a university farm (1,788 litters) and reported significant negative correlations between within-litter piglet birth weight variation and both weaning weight and pre-weaning survival. Roehe and Kalm (2000) analyzed data from a university farm collected over a five-year period (1,338 litters), and reported an increasing probability of piglet mortality as the within-litter variation in birth weight increased. However, neither of these studies used cross-fostering, which makes these results difficult to directly compare to those of the current study.

Several studies have evaluated the effects of cross-fostering to create litters with differing weight variation on pre-weaning piglet performance. However, none of these involved piglets of all birth weights reared in litters of all possible weight combinations. For example, two studies evaluated the effects of litter birth weight variation on the performance of only light birth weight piglets. English and Bilkei (2004), in a study with limited replication (10 litters per treatment), evaluated the performance of light birth weight piglets (0.9 to 1.0 kg) reared with light, average (1.2 to 1.59 kg), or heavy (> 1.6 kg) piglets in either small (8 piglets) or large (12 piglets) litters. For both litter sizes, light piglets had lower weaning weights (at 21 d of age) when reared with heavy than with light or average birth weight piglets. However, pre-weaning mortality was higher for light piglets reared with heavy compared to average or light littermates in large but not small litters. Deen and Bilkei (2004) carried out a similar study utilizing the same weight categories and litter sizes as English and Bilkei (2004) to evaluate the performance of light birth weight piglets reared with either heavy or average weight piglets. For both litter sizes, light piglets in litters with average weight littermates had greater growth to weaning than those in litters with heavy piglets. Light piglets had lower pre-weaning mortality when reared with average compared to heavy birth weight piglets in large but not small litters. Douglas et al. (2014) found that rearing light (i.e., < 1.25 kg) birth weight piglets in litters with other light piglets increased weaning weights (at 28 d of age) compared to those reared with heavier birth weight (i.e., 1.6 to 2.0 kg) piglets, however, pre-weaning mortality was not reported. The results of these studies are similar to those of the current study for Light birth weight piglets, and support the concept that light piglets reared with heavier littermates have reduced pre-weaning growth and increased pre-weaning mortality. However, none of these studies evaluated the effects of within litter weight variation on the growth or mortality of heavier piglets.

Bierhals et al. (2012) evaluated the effects of within-litter birth weight variation using light (1.0 to 1.2 kg) and medium (1.4 to 1.6 kg) birth weight piglets. Cross-fostered litters of 14 piglets were formed to compare three treatments: uniform (all light or all medium piglets), or mixed (seven light and seven medium piglets). There were no significant treatment effects on piglet growth or mortality, suggesting that neither birth weight nor within-litter variation in weight affected piglet growth or survival to weaning. However, this study excluded piglets from the lighter (< 1.0 kg) and heavier (> 1.6 kg) ends of the birth weight distribution, which constitute a significant proportion of most populations. In addition, this study had relatively limited replication, which could make it difficult to detect effects, especially on piglet mortality. These results are in contrast to the findings of most other studies, including the current one, of relatively large effects of piglet birth weight and within-litter variation on pre-weaning growth and mortality.

Milligan et al. (2001) carried out a study that involved piglets of all birth weights, but did not include all relevant combinations of either piglet weight or within-litter weight variation. In that study, cross-fostering was performed to create large (11 or 12 piglets) or small (eight or nine piglets) litters with piglets of mixed (lightest and heaviest quartiles) or uniform (two middle quartiles) weights. Piglets reared in smaller litters had greater pre-weaning growth than those in larger litters, however there were no effects of within-litter weight variation on pre-weaning growth, and neither litter size nor within-litter weight variation affected piglet mortality. It is impossible to compare these results with those of the current study, as the approach used by Milligan et al. (2001) confounded piglet birth weight with the within-litter weight variation treatments.

Huting et al. (2017) evaluated the effect of within-litter birth weight variation in light (≤ 1.25 kg) and heavy (1.50 to 2.00 kg) birth weight piglets reared in litters of uniform (only light or heavy birth weight piglets) or mixed (equal numbers of light and heavy piglets) birth weights. Similar to the current study, there was an interaction between piglet birth weight and within-litter birth weight variation treatments for pre-weaning growth and mortality. Light birth weight piglets had heavier weaning weights in uniform than in mixed weight litters. In contrast, heavy birth weight piglets had greater weaning weights in mixed than uniform litters. In addition, Huting et al. (2017) found no significant effect of within-litter birth weight variation on the pre-weaning mortality of light piglets, however, heavy piglets had lower pre-weaning mortality in mixed than uniform litters. These results are generally in line with those of the current study, suggesting a substantial effect of within-litter variation in birth weight after cross-fostering on piglet survival and growth which differed depending on birth weight. However, the study of Huting et al. (2017) did not include piglets in the middle of the birth weight distribution (between 1.25 and 1.50 kg), and only used a total of 36 litters of 12 piglets, which may not have been sufficient to detect important treatment differences in measurements such as piglet mortality.

In general, the previous research discussed above suggests that cross-fostering to reduce within-litter birth weight variation improves performance of low birth weight piglets, with some studies also finding detrimental effects on heavier piglets, which is similar to the results of the current study. However, most previous studies either did not include piglets from the full range of the birth weight distribution, or did not have sufficient replication to detect commercially relevant differences in piglet mortality. An interesting finding of the current study was that Light piglets had reduced pre-weaning growth rates in Mixed compared to Uniform litters when all piglets, including those removed for PWM, were used in the calculation but not when only weaned piglets were used. This result was most likely due to the higher PWM of Light piglets in Mixed compared to Uniform litters.

Causes and Timing of PWM and Piglet Stomach Contents

Results for the effect of LC and BWC on the causes and timing of PWM, and age of piglets at mortality, and the weight of the stomach contents of piglets that died are presented in Table 8.3. There was no effect of LC and no interaction ($P > 0.05$) between BWC and LC for any of these measurements. The only effect of BWC on the causes PWM was for the percentage due to crushing, which was greater ($P \leq 0.05$) for Medium piglets compared to the other BWC. Overall, crushing and starvation were the primary causes of PWM, accounting for 85.4, 98.5, and 100% of PWM for Light, Medium, and Heavy piglets, respectively. These results are generally in agreement with many other studies which have shown that these are the primary causes of piglet pre-weaning mortality (e.g. Dyck and Swierstra, 1987; Marchant et al., 2000). When comparing these results, it should be borne in mind that in the current study PWM due to starvation included piglets removed for low vitality scores in addition to those that died for this reason. No other studies were found that reported on the effect of piglet birth weight *per se* on the causes of pre-weaning mortality.

Timing of PWM differed ($P \leq 0.05$) between BWC. Compared to Heavy piglets, Light and Medium had a greater percentage ($P \leq 0.05$) of total PWM within the first 24 h of the study period (24 to 48 h after birth). In addition, a greater ($P \leq 0.05$) percentage of PWM for Light compared to Medium or Heavy piglets occurred during the first week after allotment. Conversely, a greater ($P \leq 0.05$) percentage of total PWM of Medium and Heavy compared to Light piglets occurred from day eight to weaning. As a result, mortality age was greatest ($P \leq$

0.05) for Heavy (9.6 d), lowest for Light (5.6 d), and intermediate ($P > 0.05$) for Medium piglets (7.2 d; Table 8.3). Similarly, Le Dividich et al. (2017) found that piglets with birth weights less than one SD below the mean had a lower average age at death than heavier piglets (1.8 and 6.9 d, respectively). Many studies have reported that the majority of piglet deaths occur within the first week after birth (e.g. Dyck and Swierstra, 1987; Su et al., 2007; KilBride et al., 2012). In the current study, this was the case for Light and Medium piglets, however, Heavy piglets had a greater percentage of PWM in the last two weeks of the study period. It is difficult to compare these results with previous literature, as the current study did not include piglet mortality within the first 24 h after birth, and no other published research has reported on the relationship between timing of piglet mortality and birth weight.

There was an effect ($P \leq 0.05$) of BWC on stomach contents, which were greatest ($P \leq 0.05$) for Medium (24.4 g), lowest ($P \leq 0.05$) for Light (13.3 g), and those of Heavy piglets were intermediate but not different ($P > 0.05$) to the other BWC (17.0 g). Hales et al. (2013) found that piglets which died within 24 h after birth had lower stomach contents than those that died later, which suggests that stomach contents should increase with time after birth. In support of this concept, Light piglets in the current study had the numerically lowest weights of stomach contents and lowest average age of mortality. On this basis, it was surprising that Heavy piglets did not have the greatest weights of stomach contents of all the BWC, as they had the highest age of mortality. However, there was a tendency ($P = 0.09$) for the percentage of Heavy piglet mortality due to starvation to be greater than the other two BWC (44.7, 23.9, and 32.7% of PWM, for Heavy, Medium, and Light piglets, respectively). Additional research is needed to verify the relationship between the weight of stomach contents of mortalities and piglet birth weight.

Conclusion

In conclusion, the results of the current study, which involved large litter sizes typical of current commercial production, suggested that cross-fostering to reduce birth weight variation within a litter was beneficial to the pre-weaning performance of Light birth weight piglets, but detrimental to the performance of Heavy piglets, and had no effect on the performance of Medium piglets. While it is often recommended to rear low birth weight piglets in litters of uniform weights, these results suggest that the effects on piglets of all weights in the population need to be considered. This study also suggests that the optimum cross-fostering method may depend on the birth weight distribution of the specific population in question. In this regard, it should be borne in mind that the treatments used in this study did not represent the typical birth weight distribution found in commercial populations.

Tables

Table 8.1. Summary of sow characteristics by litter composition treatment.

	Litter Composition[1]			
Item.	Uniform	Mixed	SEM	*P*-value
Number of litters	51	51	-	-
Average sow parity[2]	4.2	4.3	0.19	0.71
Number of sows by parity[2]				
1	0	0	-	-
2	2	3	-	-
3	3	2	-	-
4 and 5	23	23	-	-
6 and 7	23	23	-	-
Average sow body condition score[3]	3.4	3.6	0.07	0.06
Number of sows by body condition score[3]				
1.0 to 1.5	0	0	-	-
2.0 to 2.5	1	0	-	-
3.0 to 3.5	35	31	-	-
4.0 to 4.5	15	20	-	-
5	0	0	-	-
Average number of teats by functionality score[4]				
Score 1	11.3	11.5	0.23	0.55
Score 2	3.1	2.9	0.25	0.58
Score 3	0.4	0.2	0.08	0.27
Functional teats (Score 1+2)	14.4	14.4	0.1	0.99

[1]Uniform = All piglets of the same birth weight category (Light, Medium, or Heavy); Mixed = Equal numbers of piglets with Light, Medium, and Heavy birth weights.
[2]Parity = total number of litters including the one used in the study.
[3]On a scale of 1 extremely thin to 5 extremely fat.
[4]On a scale of 1 to 3: Score 1 = ideal, elongated and pointed with no visible defects; Score 2 = not ideal, not as elongated, but teat end protruded well down and with no visible defects; Score 3 = non-functional, the teat was severely damaged or visibly defective.

Table 8.2. Least-squares means for the interaction of litter composition and birth weight category treatments for piglet birth and weaning weights, pre-weaning average daily gain, and total pre-weaning mortality.

	Birth Weight Category (BWC)[1]									
	Light		Medium		Heavy					
	Litter Composition (LC)[2]							*P*-value		
Item.	Uniform	Mixed	Uniform	Mixed	Uniform	Mixed	SEM	LC	BWC	LC x BWC
Number of piglets allotted	255	255	255	255	255	255	-	-	-	-
Piglet birth weight, kg	0.86^{c}	0.86^{c}	1.28^{b}	1.28^{b}	1.69^{a}	1.69^{a}	0.008	0.96	<0.0001	0.95
Piglet weaning weight, kg	4.33^{c}	4.09^{c}	5.29^{b}	5.31^{b}	5.52^{b}	6.34^{a}	0.095	0.004	<0.0001	<0.0001
Average daily gain, kg										
All piglets[3]	0.134^{c}	0.096^{d}	0.182^{b}	0.180^{b}	0.168^{b}	0.225^{a}	0.006	0.31	<0.0001	<0.0001
Weaned piglets	0.175^{c}	0.161^{c}	0.203^{b}	0.204^{b}	0.194^{b}	0.235^{a}	0.0048	0.01	<0.0001	<0.0001
Pre-weaning mortality, %[4]	21.7^{b}	38.4^{a}	12.6^{c}	13.7^{c}	14.1^{c}	4.3^{d}	-	0.44	<0.0001	<0.0001

[a,b,c,d]Means within a row with different superscripts differ significantly at $P \leq 0.05$.

[1]Light = Piglets with birth weights between 0.50 and 1.04 kg; Medium = Piglets with birth weights between 1.05 kg and 1.50 kg; Heavy = Piglets with birth weights between 1.51 and 2.00 kg

[2]Uniform = All piglets of the same birth weight category (Light, Medium, or Heavy); Mixed = Equal numbers of piglets with Light, Medium, and Heavy birth weights.

[3]All piglets includes those weaned and removed for PWM.

[4]Pre-weaning mortality data from one litter was not included in the analysis from the Uniform/Light treatment combination due to above normal levels.

Table 8.3. Means for the effects of litter composition and birth weight category on the stomach contents of mortalities, piglet age at mortality or weaning, and causes and timing of piglet mortality, as a percentage of total pre-weaning mortality and treatment.

	Litter Composition (LC)[1]		Birth Weight Category (BWC)[2]			P-value		
Item.	Uniform	Mixed	Light	Medium	Heavy	LC	BWC	LC x BWC
Number of mortalities	120	144	150	67	47	-	-	-
Causes of mortality, % of total								
Low viability	4.2	8.3	11.3	0.0	0.0	0.99	0.99	0.99
Crushing	61.7	56.3	52.7^{b}	74.6^{a}	55.3^{b}	0.72	0.02	0.27
Starvation	30.8	34.0	32.7	23.9	44.7	0.94	0.09	0.24
Injury	2.5	0.7	2.0	1.5	0.0	0.99	0.99	0.99
Unknown	0.8	0.7	1.3	0.0	0.0	0.98	0.99	0.95
Timing of mortality, % of total[3]								
Days 1 to 2	15.0	19.4	20.7^{a}	17.9^{a}	6.4^{b}	0.96	0.01	0.22
Days 1 to 7	55.0	72.9	75.3^{a}	59.7^{b}	38.3^{b}	0.23	0.01	0.61
Days 8 to Weaning	45.0	21.7	24.7^{b}	40.3^{a}	61.7^{a}	0.23	0.01	0.61
Age of mortality, days[4]	7.2	6.1	5.6^{b}	7.2^{ab}	9.6^{a}	0.23	<0.0001	0.56
Stomach contents, g[5]	20.1	16.3	13.3^{b}	24.4^{a}	17.0^{ab}	0.21	0.0003	0.35

^{a,b}Means within a treatment and row with different superscripts differ significantly at $P \leq 0.05$.

[1]Uniform = All piglets of the same birth weight category (Light, Medium, or Heavy); Mixed = Equal numbers of piglets with Light, Medium, and Heavy birth weights.

[2]Light = Piglets with birth weights between 0.50 and 1.04 kg; Medium = Piglets with birth weights between 1.05 kg and 1.50 kg; Heavy = Piglets with birth weights between 1.51 and 2.00 kg.

[3]Days of the study period, starting 24 h after birth.

[4]From all piglets removed for PWM. Data were transformed using a square root transformation to correct for normality and homogeneity of variance of the residuals.

[5]Only from piglets that died during the study period; data were transformed using a natural log transformation to correct for normality and homogeneity of variance of the residuals.

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CHAPTER 9: Effect of rearing cross-fostered piglets in litters of differing within-litter birth weight variation on pre-weaning growth and mortality

Abstract

Cross-fostering is commonly used in the commercial swine industry to equalize either litter sizes and/or piglet birth weights within litters. However, there is limited published information on optimum cross-fostering methods. This study evaluated within-litter birth weight variation after cross-fostering for effects on piglet pre-weaning mortality (PWM) and growth. Piglets were classified by Birth Weight Category (BWC): Light (L; < 1.0 kg), Medium (M; 1.0 to 1.5 kg), or Heavy (H; 1.5 to 2.0 kg). A randomized complete block design was used; blocking factors were farrowing day and sow parity, body condition score, and functional teat number. All litters consisted of 14 piglets; all piglets were cross-fostered. Six Litter Composition (LC) treatments were compared: Uniform (14 piglets of the same BWC; L, M, or H); Mixed L+M (7 L and 7 M piglets); Mixed M+H (7 M and 7 H piglets); Mixed L+M+H (3 L, 6 M, and 5 H piglets). Piglets were weighed 24 h after birth and randomly allotted to LC treatments from within BWC. There were 47 blocks of 6 litters (total 282 litters and 3,948 piglets). Weaning weights were collected at 18.7 ± 0.64 d of age; all PWM was recorded. Individual piglet weight data were analyzed using PROC MIXED of SAS; models included fixed effects of BWC, LC, the interaction, and random effects of sow/litter within block. Individual piglet PWM data were analyzed using PROC GLIMMIX of SAS as binary response data; models included fixed effects of BWC, LC, and the interaction. There were LC by BWC interactions ($P \leq 0.05$) for PWM and weaning weight. Light piglets in Uniform litters had similar ($P > 0.05$) PWM, but greater ($P \leq 0.05$) weaning weights than those in Mixed LC treatments (L+M or L+M+H). Heavy piglets in Uniform litters had greater ($P \leq 0.05$) PWM and lower ($P \leq 0.05$) weaning weights than in

Mixed L+M+H litters, but similar ($P > 0.05$) PWM and weaning weights in Mixed M+H litters. Pre-weaning mortality of M piglets in Uniform litters was greater ($P \leq 0.05$) than in Mixed L+M litters, but similar ($P > 0.05$) to Mixed M+H and L+M+H litters. Weaning weights of M piglets in Uniform litters were greater ($P \leq 0.05$) than in Mixed M+H litters, and similar ($P > 0.05$) to Mixed L+M and L+M+H litters. In conclusion, increasing the average weight of littermates after cross-fostering generally decreased weaning weights and increased PWM within each BWC.

Introduction

Pre-weaning mortality levels on commercial sow farms have increased over recent years and currently average around 10 to 15% of piglets born alive (PigChamp, 2004, 2019; SEGES, 2017; Agriculture and Horticulture Development Board, 2020). This represents a major economic loss to producers and is also a significant animal welfare concern. This increase in pre-weaning mortality has been associated with the increases in litter sizes that have occurred over the same time period (PigChamp, 2004, 2019; SEGES, 2017; Agriculture and Horticulture Development Board, 2020). Larger litters have lower average piglet birth weights and an increased number of low birth weight piglets (i.e., < 1 kg; Tribout et al., 2003; Nielsen et al., 2013; Camargo et al., 2020) which have higher levels of mortality compared to heavier littermates (Herpin et al., 2002). In addition, it is increasingly common for the total number of piglets born alive within a litter to exceed the number of functional teats on the sow. As a consequence, developing practical approaches to rearing this increased number of piglets is important.

Cross-fostering has been widely used in commercial production to reduce competition between piglets by equalizing litter sizes and/or reducing piglet weight variation within a litter. In practice, there are a number of potential approaches to cross-fostering that can be used.

However, not all of these approaches have been studied for their effect on piglet pre-weaning growth and survival. In addition, the studies that have been published are often of limited relevance for development of commercial protocols. Many studies have used limited replication and, consequently, do not have the statistical power to detect practically important differences in piglet performance, particularly pre-weaning mortality (e.g. Milligan et al., 2001; Huting et al., 2017). Other studies have reported retrospective analyses of relatively large commercial datasets (e.g. Roehe and Kalm, 2000; Zindove, 2011). However, in these studies the methods used for cross-fostering were generally poorly defined, and were often confounded with other factors such as piglet birth weight or litter size. In addition, most previous research has been carried out with litter sizes that are relatively small (typically ≤ 12 piglets per litter; e.g. English and Bilkei, 2004; Huting et al., 2017). However, genetic improvements over recent decades have resulted in a substantial increase in average litter size (Su et al., 2007), with the total number of piglets born currently being around 15 to 17 piglets per litter (SEGES, 2017; PigChamp, 2019). Only two studies (Douglas et al., 2014; Vande Pol et al., 2020) utilized litter sizes that are typical of those in current commercial production.

A further limitation of the published cross-fostering research is that the majority of studies have focused on a limited range from the piglet birth weight distribution, often only reporting effects on light birth weight piglets, making the results of limited application (e.g. English and Bilkei, 2004; Bierhals et al., 2012; Douglas et al., 2014). In theory, light piglets should be better able to compete for teat access when they are reared among piglets of similar weight. This approach would also result in rearing heavier birth weight piglets in litters of reduced weight variation. However, there has been limited research evaluating the effect of within-litter weight variation after cross-fostering on piglet competition within the litter and, ultimately, on pre-weaning performance of the entire population. Vande Pol et al. (2020) found that increased within-litter weight variation improved pre-weaning performance of heavier birth weight piglets but reduced performance of lighter piglets. However, in that study, the within-litter weight variations compared were not all typical of those utilized in commercial production, and did not represent all possible combinations of piglet weights.

Given the considerable variation in the methodology used in previous research, it is not surprising that the results of historical cross-fostering studies are often contradictory. Therefore, there is a need for a comprehensive research-based evaluation of the various components of cross-fostering to provide objective data for the development of optimum protocols to maximize piglet pre-weaning performance. The objective of the current study was to evaluate the effect of rearing piglets in cross-fostered litters of differing birth weight distributions on pre-weaning performance under commercial conditions, using litter sizes typical of current commercial production.

Material and Methods

This study was carried out on a commercial sow facility of The Maschhoffs, LLC, located near Beardstown, IL, USA. Protocols for this study were approved by the University of Illinois Institute of Animal Care and Use Committee prior to the start of the research.

Animals and Management

The sows used were from standard commercial crossbred lines that had been mated to commercial sire lines. Housing and management of sows and piglets were generally in line with commercial procedures and practices. The facilities used consisted of rooms with 48 individual farrowing crates and pens. Farrowing pen dimensions were 1.52 m x 2.07 m (total pen floor space of 3.15 m^2), with solid side walls and woven metal flooring. A farrowing crate was located in the center of each pen, with dimensions of 0.55 m x 1.95 m (floor space within the crate of 1.07 m^2). The thermostat in the farrowing rooms was set at 22.4°C on the day of farrowing and subsequently reduced to 18°C for the duration of the study. Room temperature was maintained using heaters, evaporative coolers, and fan ventilation as needed. Sows were moved into the farrowing facilities around d 112 of gestation. All sows within a farrowing room had been inseminated on the same day and were induced on d 114 to farrow on d 115 of gestation using 2 cc of prostaglandin F2α (given at 0600 h; Lutalyse®, Pfizer Animal Health US).

During gestation and lactation, sows were fed diets formulated to meet or exceed the nutritional requirements proposed by the National Research Council (2012). From entry into the farrowing facility to the start of farrowing, sows were fed 1 kg of feed twice each day (at 0600 h and 1400 h). Subsequently, sows had *ad libitum* access to feed throughout lactation via a sow-operated feed dispenser attached to the feed trough. Sows and piglets had *ad libitum access* to water via nipple-type drinkers located in the sow feeding trough and farrowing pen, respectively. Standard pig processing tasks (tail docking, physical castration of males, iron and antibiotic injections) were carried out at approximately five days after birth. Sows and litters were taken off-test when piglets reached 19 or 20 d of age, depending on farrowing date, and piglets were weaned at 21 d of age.

Pre-allotment Data Collection

Sow parity, genetic line, body condition score (on a scale of 1 = extremely thin to 5 = extremely fat), and number of teats and teat functionality score (Score 1 = ideal, elongated and pointed with no visible defects; Score 2 = not ideal, not as elongated, but with no visible defects; Score 3 = non-functional, the teat was severely damaged or visibly defective) were determined on all sows two days prior to allotment. On the day after farrowing, piglets were weighed individually. Weight and gender were recorded, and each piglet was given a uniquely numbered ear tag. Piglets that were considered by the investigators to be non-viable were weighed, but not used in the study.

Experimental Design and Treatments

Piglets were assigned to one of three Birth Weight Categories (BWC): Light (L) = 0.50 to 1.04 kg; Medium (M) = 1.05 to 1.50 kg; Heavy (H) = 1.51 to 2.00 kg. The study utilized a randomized complete block design with six Litter Composition (LC) treatments: Uniform = all piglets in the litter from either the L, M, or H category; Mixed L+M = equal numbers of L and M piglets; Mixed M+H = equal numbers of M and H piglets; Mixed L+M+H = 3 L, 6 M, and 5 H piglets. The number of piglets from each BWC of the Mixed L+M+H treatment was approximately similar to the birth weight distribution of the population of all piglets weighed. The maximum weight for the Light category (i.e., 1.0 kg) represented the birth weight below which pre-weaning mortality increases substantially (Zotti et al., 2017). The minimum weight for the Heavy category (i.e., 1.5 kg) represented the weight above which pre-weaning mortality is generally unaffected by birth weight (Zotti et al., 2017). All litters had 14 piglets, and all piglets in these litters were cross-fostered. Piglets weighing < 0.50 kg or > 2.00 kg were not used in the study. Sows within a block were of a similar parity (± 1; no parity 1 gilts were used), a similar body condition score (± 1), and a similar number of functional teats (± 1; score 1 and 2). Sow genetic line was balanced across LC treatments over the entire study period.

Allotment Process

Allotments were carried out on the day after farrowing immediately after the piglets had been weighed. The allotment process was carried out in two stages; firstly, piglets were allotted to treatments to form litters of 14 and secondly, sows were allotted to litters. Litters within a block were formed to have no more than three littermates within a litter, equal numbers of piglets of each gender (± 1), and similar mean birth weights within BWC and gender (± 0.05 kg). This was accomplished by randomly allotting piglets to LC treatments from within each BWC and gender. Piglets were moved between litters as necessary to meet the piglet allotment restrictions above. After the piglets were allotted, six sows were selected on the basis of the sow blocking factors described above and randomly allotted to these litters.

Measurements

Piglets were weighed again at the end of the test period (weaning weight; 19 or 20 d of age), and average daily gain was calculated. Litters were checked daily and all piglets were assigned a vitality score (on a scale of 1 to 4): Score 1 = Emaciated and piglet showed signs of weakness and lethargy; Score 2 = Very thin and piglet showed some signs of lethargy, but still able to nurse; Score 3 = Thin but piglet having high energy levels and normal behavior; Score 4 = Ideal with piglet having high energy levels and normal behavior. Piglets with a vitality score 1 were euthanized; those with a score of 2 were removed from the litter, placed on a non-test sow with small piglets, and recorded as a morbidity; those with a score of 3 were treated according to farm protocol but remained on the study; those with a score 4 were not treated and remained on the study. All piglets removed during the study period due to low vitality score or death were considered as pre-weaning mortalities (PWM). If a piglet was removed from the study due to PWM, the date, tag number, vitality score, weight, and cause of PWM were recorded. Necropsies were performed on all piglets that died to determine cause of death. Full and empty stomach weights were measured and used to calculate the weight of stomach contents.

Statistical Analysis

All data were analyzed using SAS v. 9.4 (SAS Inst. Inc., Cary, NC). This study utilized a randomized complete block design with 47 replicates/blocks, for a total of 282 sows/litters and 3,948 piglets used in the study. Blocks consisted of six sows/litters, with one litter of each LC treatment. The PROC UNIVARIATE procedure of SAS was used to verify normality and homogeneity of variances of the residuals. All variables that conformed to the assumptions of normality and homogeneity (directly or through transformation of the data) were analyzed using the PROC MIXED procedure of SAS (Littell et al., 1996). Piglet weight data, stomach contents of mortalities, and average mortality age were analyzed with PROC MIXED using individual piglet data with models including the fixed effects of BWC, LC, the interaction, and the random effects of sow/litter within block. Pre-weaning mortality data were analyzed with PROC GLIMMIX with individual piglet binary response data with the model including the fixed effects of BWC, LC, and the interaction. Least-squares means for the effects of LC and BWC were separated using the PDIFF option of SAS, being considered different at $P \leq 0.05$. Relationships between the average weight of all littermates (littermate weight) and weaning weight and PWM were determined for each BWC using regression analysis. For weaning weight, PROC REG of SAS was used with littermate weight, BWC, and the interaction as the independent variables. Pre-weaning mortality was the dependent binary response variable in a non-linear regression analysis conducted using PROC Logistic of SAS, with the same independent variables as for weaning weight.

Results and Discussion

Sow Parameters

A summary of sow parameters for each of the LC treatments are presented in Table 9.1. There were no differences ($P > 0.05$) between LC for sow parity, body condition score, or number of functional teats (Score 1 and/or 2). All sows were between parity 3 and 8, with averages for each LC treatment being between 4.4 and 4.7 ($P > 0.05$). Average sow body condition scores were between 3.7 and 3.9 for the LC treatments ($P > 0.05$). The average number of functional teats (Scores 1 + 2) were between 14.5 and 14.7 for all LC treatments. The number of non-functional teats (Score 3) were different ($P \leq 0.05$) across LC treatments, however, these differences were relatively small and were not expected to have any effect on piglet performance.

In general, the sows used in this study were typical of those in contemporary commercial production. Maes et al. (2004) surveyed sow body condition scores on three commercial production farms using the same five-point scale as in the current study, and reported an average score at farrowing of 3.2. This value is somewhat lower than the average scores in the current study which ranged between 3.7 and 3.9 (Table 9.1). Kim et al. (2005) reported that the average number of teats for Duroc, Landrace, and Yorkshire gilts were 12.5, 14.9, and 13.7, respectively, which encompasses the range found in the current study, which utilized cross-bred sows of Landrace and Yorkshire origin. In the current study, the percentage of the total number of teats with functionality scores of 1, 2, and 3 (averaged across all LC treatments) were 84.3, 13.8, and 2.0%, respectively. These results are similar to the study of Balzani et al. (2016), which reported subjective teat functionality scores in a population of cross-bred sows; 82% of teats were scored as perfectly functional, 16% as partially functional, and 0.2% as completely non-functional.

Piglet Weights and Pre-weaning Mortality

There were LC by BWC treatment interactions ($P \leq 0.05$) for piglet weaning weights, average daily gain (ADG), and pre-weaning mortality rates (PWM) and therefore, the interaction subclass means are presented in Table 9.2. By design, L piglets had the lowest ($P \leq 0.05$) birth weights, and H piglets the greatest ($P \leq 0.05$), with M piglets being intermediate to and different ($P \leq 0.05$) from the other two BWC. However, within each of the BWC, piglet birth weights were similar ($P > 0.05$) across the respective LC treatments. Across all LC treatments, L piglets had the lowest weaning weights ($P \leq 0.05$), H piglets had the greatest ($P \leq 0.05$), and M piglets were intermediate and different ($P \leq 0.05$) from the other two BWC (Table 9.2).

Pre-weaning mortality of L piglets was similar ($P > 0.05$) across all three LC treatments (Table 9.2) and was greater ($P \leq 0.05$) than all LC treatments involving M and H piglets. However, weaning weight of L piglets was greater ($P \leq 0.05$) for the Uniform L treatment than the Mixed L+M and Mixed L+M+H, which were similar ($P > 0.05$; Table 9.2). The ADG of all piglets (including mortalities) and of weaned piglets followed the same pattern, being greatest ($P \leq 0.05$) for the Uniform L treatment and similar ($P > 0.05$) for the other two LC treatments.

Pre-weaning mortality of M piglets was greater ($P \leq 0.05$) for the Mixed M+H and Uniform M treatments compared to the Mixed L+M treatment, with Mixed L+M+H being intermediate and not different ($P > 0.05$) to any of the other three LC treatments involving M piglets (Table 9.2). Conversely, weaning weight of M piglets was greater ($P \leq 0.05$) for the Mixed L+M and Uniform M treatments compared to the Mixed M+H treatment, with the Mixed L+M+H treatment being intermediate and not different ($P > 0.05$) to any of these other LC treatments.

Pre-weaning mortality of H piglets was lower ($P \leq 0.05$) for the Mixed L+M+H treatment compared to Uniform H and Mixed M+H treatments, which were similar ($P > 0.05$). In contrast, weaning weight of H piglets was greater ($P \leq 0.05$) for the Mixed L+M+H treatment compared to the Uniform H treatment, with the Mixed M+H treatment being intermediate and not different ($P > 0.05$) to these other two LC treatments. For both M and H piglets, the ADG of all piglets (including mortalities) and weaned piglets generally followed a similar pattern to the weaning weights (Table 9.2).

A number of studies have reported on pre-weaning piglet performance of specific within-litter birth weight variation treatments formed by cross-fostering. However, none of these studies involved piglets of all birth weights reared in litters of all possible weight combinations. Huting et al. (2017) evaluated light (≤ 1.25 kg) and heavy (1.50 to 2.00 kg) piglets reared in litters of uniform (12 light or 12 heavy) or mixed (6 light and 6 heavy) birth weights. Similar to the current study, light birth weight piglets had heavier weaning weight in uniform than in mixed weight litters, whereas the opposite was the case for heavy piglets, which had lower weaning weight in uniform than mixed weight litters. In addition, Huting et al. (2017) found that heavy piglets had lower mortality in mixed than uniform litters, however, there was no effect for light piglets. These results are generally in line with those of the current study, suggesting a substantial effect of within-litter variation in birth weight after cross-fostering on piglet survival and growth, with effects differing depending on piglet birth weight. However, the study of Huting et al. (2017) did not include piglets with birth weights between 1.25 and 1.50 kg, and the size of the cross-fostered litters was only 12 piglets, which is below typical levels seen in current commercial production.

Vande Pol et al. (2020) utilized cross-fostering to create litters of 15 piglets with either uniform (all Light, Medium, or Heavy) or mixed (5 Light, 5 Medium, and 5 Heavy) birth weights, using identical definitions for the birth weight categories as the current study (0.5 to 1.0, 1.0 to 1.5, and 1.5 to 2.0 kg, respectively). Light piglets had reduced pre-weaning mortality in Uniform litters, whereas Heavy piglets had increased pre-weaning mortality and reduced weaning weight in Uniform litters, with no effect of within-litter weight variation on the performance of Medium piglets. For the current study, while there were no significant effects on PWM for L piglets, this was most likely due to the low number of L piglets in the Mixed L+M+H treatment, as the means were numerically different to an extent that would be commercially relevant (5.6 percentage units higher than the Uniform L treatment). In general, the results of Vande Pol et al. (2020) and the current study suggest beneficial effects of reducing littermate weight on piglet pre-weaning performance.

Some studies have evaluated the effects of litter birth weight variation on the performance of only light birth weight piglets. English and Bilkei (2004) and Deen and Bilkei (2004) utilized the same birth weight classifications (light - 0.9 to 1.0 kg; average - 1.2 to 1.59 kg; and heavy - > 1.6 kg), and litter sizes (small - 8 piglets; large - 12 piglets). English and Bilkei (2004) reared light piglets with other light, average, or heavy piglets, whereas Deen and Bilkei (2004) reared light piglets with only average or heavy weight piglets. For both studies and within both litter sizes, light piglets had lower weaning weights (at 21 d of age) when reared with heavy than with light or average piglets. In addition, in both studies, light piglets also had greater pre-weaning mortality when reared with heavy compared to average or light littermates in large but not small litters. Similarly, Douglas et al. (2014) found that rearing light (< 1.25 kg) birth weight piglets in litters with other light piglets increased weaning weights (at 28 d of age) compared to those reared with heavier (1.6 to 2.0 kg) piglets, however, pre-weaning mortality was not reported. The results of these studies are similar to those of the current study for Light birth weight piglets, and support the concept that Light piglets have improved pre-weaning performance when reared with lighter littermates. However, none of these studies evaluated these effects on heavier piglets, and also utilized relatively small litter sizes.

In contrast to the results of the current study, two studies found no effect of either piglet birth weight or within-litter weight variation on pre-weaning performance. Bierhals et al. (2012) created cross-fostered litters of 14 piglets with uniform [all light (1.0 to 1.2 kg) or all medium (1.4 to 1.6 kg) piglets], or mixed (seven light and seven medium piglets) birth weights. Milligan et al. (2001) compared litters with the lightest and heaviest weight quartiles (mixed weight) to those including the two middle quartiles (uniform weight). Some of the inability in these studies to detect differences in piglet performance, particularly pre-weaning mortality, may be due to limited replication. In addition, Bierhals et al. (2012) excluded a large proportion of the piglet birth weight distribution (< 1.0 or > 1.6 kg), and Milligan et al. (2001) confounded within-litter variation treatments with piglet birth weight.

Several studies have conducted retrospective analyses of datasets to determine the effect of litter weight variation at birth on piglet performance, without any specific cross-fostering treatments. A number of these studies found negative correlations between within-litter piglet birth weight variation and weaning weight (Zindove, 2011) and pre-weaning survival (Roehe and Kalm, 2000; Milligan et al., 2002a,b; Zindove, 2011). In contrast, Wolf et al. (2008) found that when average piglet birth weight was accounted for in the statistical model, within-litter birth weight variation (estimated using the CV of birth weights within the litter) had no effect on pre-weaning mortality levels. However, it is difficult to compare the results of these retrospective analyses with those of the current study, as they did not control for potential confounding factors such as average piglet birth weight or litter size.

Causes and Timing of PWM and Piglet Stomach Contents

Results for the effect of LC and BWC on the causes and timing of piglet mortality (expressed as a percentage of total mortality within each LC and BWC treatment), age of piglets at mortality, and the weight of the stomach contents of mortalities are presented in Table 9.3. There were no interactions ($P > 0.05$) between BWC and LC for any of these measurements, therefore, only the main effect means have been presented. There were no effects ($P > 0.05$) of LC on the causes or timing of piglet mortality. The only effect of BWC on the causes of mortality was for starvation, with the percentage of mortalities being greater ($P \leq 0.05$) for L and M compared to H piglets. In addition, compared to M piglets, a greater ($P \leq 0.05$) percentage of L and H piglets died within the first 24 h of the study period (day 1 to 2; 24 to 48 h after farrowing). As a result, age of mortality was greater ($P \leq 0.05$) for M compared to L or H piglets, although differences were relatively small (6.1, 5.1, and 5.1 d, respectively). There was an effect ($P \leq 0.05$) of both LC and BWC on the weight of stomach contents of mortalities. For BWC, piglet stomach contents were greater ($P \leq 0.05$) for M and H piglets compared to L piglets. For LC, the Uniform M and Uniform H treatments had greater ($P \leq 0.05$) stomach contents than the Uniform L, Mixed L+M, and Mixed L+M+H treatments, with the Mixed M+H treatment being intermediate and not different to the other LC treatments ($P > 0.05$).

In the current study, crushing and starvation were the primary causes of piglet mortality, accounting for 94.3, 94.0, and 91.8% of all mortality for L, M, and H piglets, respectively. These results are generally in agreement with many other studies (e.g. Dyck and Swierstra, 1987; Marchant et al., 2000). It should be borne in mind that in the current study piglets that were removed from the study due to morbidity (piglets with a vitality score of 1 or 2; data not reported) were included with mortality data, as the investigator deemed that these piglets were likely to die without intervention. Morbidities accounted for 15.2% of all mortality and were all classified as starvation as the cause of mortality. Vande Pol et al. (2020) reported that a greater percentage of mortality of Medium weight piglets was due to crushing than for either Heavy or Light piglets, and that there was a tendency ($P = 0.09$) for Heavy piglets to have a greater percentage of mortality due to starvation than Medium or Light piglets. The results of Vande Pol et al. (2020) are opposite of those found in the current study, where H piglets had the lowest percentage of mortality due to starvation, and tended to have a greater percentage of mortality due to crushing. It is not clear why the results of these relatively similar studies differed for the effect of piglet birth weight on the causes of mortality, and further research in this area is necessary.

Many studies have reported that the majority of piglet deaths occur within the first week after birth (e.g. Dyck and Swierstra, 1987; Su et al., 2007; KilBride et al., 2012). This is in agreement with the current study, which found that between 70.0 and 76.8% of piglet mortality occurred within the first seven days of the study period, across all LC treatments. However, the current study also found that the percentage of total mortality that occurred within the first day of the study period was lower and the average age of mortality was higher for M than either L or H piglets, which were similar for these measurements. There is very limited published research on the relationship between birth weight and timing of piglet mortality, however, the results of the current study are in contrast with those of several other studies. Le Dividich et al. (2017) found that piglets with birth weights less than one SD below the mean had a lower average age at death than heavier piglets (1.8 and 6.9 d, respectively). Vande Pol et al. (2020) also found that low birth weight piglets (0.5 to 1.0 kg) had a lower age of mortality than heavy piglets (1.5 to 2.0 kg), with medium piglets (1.0 to 1.5 kg) being intermediate (5.6, 9.6, and 7.2 d, respectively). Further research would be needed to establish the effects of piglet birth weight on the causes and timing of pre-weaning mortality.

In the current study, L piglets had lower weights of stomach contents than M or H piglets, which were similar. Vande Pol et al. (2020) utilized the same birth weight categories, and found that Light piglets had lower weights of stomach contents compared to Medium but not Heavy piglets. However, in that study there was also a tendency ($P = 0.09$) for a greater percentage of Heavy piglet mortality to be due to starvation than for Medium or Light piglets. This is opposite to the current study, where H piglets had the lowest rate of starvation (Table 9.3). In the current study, there were also some differences in the weight of piglet stomach contents between LC treatments. Most of these differences could be explained by the differences in average piglet birth weight between LC treatments, and the higher percentage of deaths due to starvation for Light piglets.

Regression Analyses

The results described above (Table 9.2) suggested that within each BWC, increases in the weight of other piglets in the litter were associated with decreases in weaning weight and increases in PWM. Consequently, regression analyses were conducted to evaluate the relationship between average littermate weight and weaning weights and PWM. For these analyses, littermate weight was calculated for each individual piglet, as the average weight of all other piglets in the cross-fostered litter. The probability of PWM was estimated using the log odds from the non-linear regression analysis by calculating the log odds for each BWC and littermate weight combination, taking the exponent of these values, and converting using probability = odds/(1+odds), and graphing these calculated probabilities against littermate weight for each BWC.

The results of the analysis for piglet weaning weight are presented in Table 9.4 and illustrated in Figure 9.1. Intercepts and slopes for all BWC were significantly different to zero ($P \leq 0.05$). Intercepts were different ($P \leq 0.05$) between all BWC; L piglets were the lowest, H were greatest, and M piglets were intermediate. However, slopes were similar ($P > 0.05$) between the three BWC. The results of the analysis for PWM are presented for each BWC as the linear relationship between littermate weight and the log odds of PWM in Table 9.5, and illustrated as the probability of PWM in Figure 9.2. Intercepts and slopes of the log odds of PWM for all BWC were significantly different to zero ($P \leq 0.05$). Intercepts were different ($P \leq 0.05$) between all BWC; L piglets had the greatest, H piglets had the lowest, and M piglets were intermediate. The slopes of the log odds were similar ($P > 0.05$) for L and M piglets, and greater ($P > 0.05$) for H piglets (Table 9.5). The predicted probability of PWM (Figure 9.2) increased with littermate weight for all BWC. Predicted probabilities of PWM for L piglets increased from 19.9 to 33.7% as littermate weight increased from 0.80 to 1.40 kg. In contrast, this increase was 8.0 to 15.0% for M piglets as littermate weight increased from 1.0 to 1.6 kg, and from 2.3 to 12.1% for H piglets as littermate weight increased from 1.3 to 1.8 kg (Figure 9.2).

The results of these regression analyses show a relatively large unfavorable effect of increasing littermate weight on both weaning weight and PWM across all BWC. While heavier piglets had greater weaning weights, increasing littermate weight decreased weaning weight for all BWC to a similar extent. This suggests that cross-fostering to modify within-litter weight variation will not have much effect on average weaning weight across the whole population. However, the rate of increase in PWM with increasing littermate weight was of a greater magnitude for Heavy compared to Light or Medium piglets. This suggests that Heavy piglets will experience a greater decrease in PWM from reducing littermate weight than the effect on PWM of reducing littermate weight for Medium or Light piglets. By definition, in any finite population of piglets, reducing littermate weight for one BWC must increase littermate weight for piglets for other BWC. On this basis, decisions on the optimum cross-fostering procedure for any situation can only be made by considering the birth weight distribution of the population in question. In the commercial population used in this study, light piglets (birth weights < 1 kg) only accounted for ~15% of the population, whereas medium (1.0 to 1.5 kg) and heavy piglets (> 1.5 kg) were ~45 and ~40% of the population, respectively, which is similar to distributions found in previous commercial studies (Feldpausch et al., 2019; Vande Pol et al., 2020). Therefore, combining the PWM results from the current study with this distribution of birth weights suggests that a cross-fostering strategy that minimizes littermate weights for heavy piglets would produce a greater total number of piglets weaned than one that favored light or medium piglets. As heavy piglets have a greater post-weaning growth potential and lower mortality than their lighter littermates (Fix et al., 2010a,b), such an approach would also be potentially beneficial for post-weaning performance as it would increase the number of heavy weight piglets weaned.

Conclusions

The results of this study suggest that the increased competition between piglets associated with increases in the average weight of littermates after cross-fostering resulted in increased mortality and decreased weaning weight for all BWC. The reduction in weaning weight with increasing littermate weight were similar for the three BWC but increases in mortality with littermate weight were greater in magnitude for Heavy than Light or Medium piglets. This suggests that optimal cross-fostering strategies to maximize overall piglet performance should be developed based on the birth weight distribution of the population, as littermate weight cannot be reduced for all piglets.

Tables and Figures

Table 9.1. Summary of sow characteristics by litter composition treatment.

Item.	Litter Composition[1] Uniform L	Uniform M	Uniform H	Mixed L+M	Mixed M+H	Mixed L+M+H	SEM	*P*-value
Average sow parity[2]	4.5	4.4	4.6	4.5	4.4	4.7	0.18	0.82
Number of sows by parity[2]								
Parity 1 and 2	0	0	0	0	0	0	-	-
Parity 3	1	4	2	1	2	3	-	-
Parity 4 and 5	26	19	21	21	23	16	-	-
Parity 6 and 7	16	23	22	23	20	25	-	-
Parity 8	4	1	2	2	2	3	-	-
Average sow body condition score[3]	3.8	3.7	3.7	3.8	3.7	3.9	0.09	0.67
Number of sows by body condition score[3]								
1.0 to 1.5	0	0	0	0	0	0	-	-
2.0 to 2.5	0	0	0	2	1	0	-	-
3.0 to 3.5	23	27	28	18	26	21	-	-
4.0 to 4.5	19	16	12	22	15	21	-	-
5.0	5	4	7	5	5	5	-	-
Average number of teats[4]								
Score 1	12.5	12.6	12.6	12.6	12.4	12.6	0.19	0.73
Score 2	2.2	2.0	2.0	1.9	2.2	2.4	0.17	0.39
Score 3	0.2^{b}	0.4^{ab}	0.3^{ab}	0.3^{ab}	0.3^{ab}	0.6^{a}	0.09	0.03
Functional teats (Score 1+2)	14.6	14.6	14.7	14.5	14.6	14.7	0.11	0.91

[a,b]Means within a row with differing superscripts differ at $P \leq 0.05$.

[1]Uniform = 14 piglets of the same birth weight category (L = 0.50 to 1.04 kg, M = 1.05 to 1.50 kg, or H = 1.51 to 2.00 kg); Mixed L+M = 7 L and 7 M piglets; Mixed M+H = 7 M and 7 H piglets; Mixed L+M+H = 3 L, 6 M, and 5 H piglets.

[2]Parity = total number of litters including the one used in the study.

[3]On a scale of 1 extremely thin to 5 extremely fat.

[4]On a scale of 1 to 3: Score 1 = ideal, elongated and pointed with no visible defects; Score 2 = not ideal, teat end less elongated, but no visible defects; Score 3 = non-functional, teat severely damaged or visibly defective

Table 9.2. Least-squares means for the interaction effects of litter composition and birth weight category on piglet weight, average daily gain, and pre-weaning mortality.

	Birth weight category (BWC)[1]											
	Light (L)			Medium (M)				Heavy (H)				
	Litter composition (LC)[2]											
		Mixed			Mixed				Mixed			*P*-value
Item.	Uniform	L+M	L+M+H	Uniform	L+M	M+H	L+M+H	Uniform	M+H	L+M+H	SEM	LC x BWC
Number of piglets	658	329	141	658	329	329	280	658	329	237	-	-
Piglet weight, kg												
Birth	0.89^{c}	0.89^{c}	0.89^{c}	1.28^{b}	1.28^{b}	1.28^{b}	1.28^{b}	1.69^{a}	1.69^{a}	1.69^{a}	0.007	0.99
Weaning	4.54^{e}	4.25^{f}	4.07^{f}	5.43^{c}	5.57^{c}	5.15^{d}	5.31^{cd}	6.14^{b}	6.26^{ab}	6.56^{a}	0.079	<0.01
Average daily gain, kg												
Weaned piglets	0.194^{f}	0.179^{g}	0.169^{g}	0.221^{d}	0.230^{cd}	0.207^{ef}	0.215^{de}	0.238^{bc}	0.245^{ab}	0.260^{a}	0.004	<0.01
All piglets[3]	0.154^{g}	0.135^{h}	0.122^{h}	0.200^{e}	0.215^{cd}	0.185^{f}	0.198^{def}	0.222^{bc}	0.233^{b}	0.257^{a}	-	<0.01
Pre-weaning mortality, %	22.8^{a}	26.7^{a}	28.4^{a}	12.2^{bc}	7.1^{d}	14.6^{b}	10.0^{bcd}	9.6^{cd}	5.8^{d}	1.7^{e}	-	<0.01

^{a,b,c,d,e,f,g,h}Means with differing superscripts differ at $P \leq 0.05$.

[1]Light = Piglets with birth weights between 0.50 and 1.04 kg; Medium = Piglets with birth weights between 1.05 and 1.50 kg; Heavy = Piglets with birth weights between 1.51 and 2.00 kg.

[2]Uniform = 14 piglets of the same birth weight category (L = 0.50 to 1.04 kg, M = 1.05 to 1.50 kg, or H = 1.51 to 2.00 kg); Mixed L+M = 7 L and 7 M piglets; Mixed M+H = 7 M and 7 H piglets; Mixed L+M+H = 3 L, 6 M, and 5 H piglets.

[3]Transformed data using a square transformation to correct for normality and homogeneity of variance of the residuals.

Table 9.3. Least-squares means for the effect of litter composition and birth weight category on the causes and timing of piglet mortality as a percentage of total mortality within litter composition and birth weight category, and the stomach contents of piglets that died during the study period.

	Litter Composition (LC)[1]						Birth weight category (BWC)[2]			*P*-value[3]	
Item.	Uniform L	Uniform M	Uniform H	Mixed L+M	Mixed M+H	Mixed L+M+H	L	M	H	LC	BWC
Number of mortalities	150	80	63	120	67	72	283	183	86	-	-
Cause of mortality, % of total											
Crushed	79.3	77.5	85.7	70.8	86.6	70.8	74.2	79.2	86	0.06	0.06
Starvation	17.3	13.8	6.3	20.8	10.4	22.2	20.1[a]	14.8[a]	5.8[b]	0.08	0.01
Other	3.3	8.8	7.9	6.7	1.5	5.6	5.3	5.5	5.8	0.36	0.98
Time of mortality, % of total											
Day 1 to 2	18.7	8.8	23.8	15	17.9	11.1	18.0[a]	8.7[b]	24.4[a]	0.17	0.003
Day 1 to 7	78	73.8	77.8	71.6	76.1	70.8	76.8	70	75.6	0.6	0.26
Day 8 to weaning	22	26.3	22.2	28.3	23.8	29.2	23.2	29.9	24.4	0.75	0.23
Age of mortality, days[4]	4.7	5.7	5.1	6.2	5.6	5.5	5.1[b]	6.1[a]	5.1[b]	0.54	0.05
Stomach contents, g[5]	14.2[b]	28.1[a]	32.1[a]	18.1[b]	19.4[ab]	16.2[b]	13.7[b]	25.4[a]	29.1[a]	0.01	0.001

[a,b]Means with differing superscripts differ at $P \leq 0.05$.

[1]Uniform = 14 piglets of the same birth weight category (L = 0.50 to 1.04 kg, M = 1.05 to 1.50 kg, or H = 1.51 to 2.00 kg); Mixed L+M = 7 L and 7 M piglets; Mixed M+H = 7 M and 7 H piglets; Mixed L+M+H = 3 L, 6 M, and 5 H piglets.

[2]L = birth weights between 0.50 and 1.04 kg; M = birth weights between 1.05 kg and 1.50 kg; H = birth weights between 1.51 and 2.00 kg.

[3]All LC by BWC interaction *P*-values were > 0.05.

[4]Transformed data using an inverse square root transformation to correct for normality and homogeneity of variance of the residuals.

[5]Transformed data using a log transformation to correct for normality and homogeneity of variance of the residuals.

Table 9.4. Linear regression for the effect of piglet birth weight and littermate weight on weaning weight.

Birth weight category	Intercept	Slope	SE				*P*-value			
			L vs M intercept	M vs H intercept	L vs M slope	M vs H slope	L vs M intercept	M vs H intercept	L vs M slope	M vs H slope
Light (L)[1]	5.49	-1.08	0.364	0.438	0.316	0.305	<0.0001	0.03	0.71	0.60
Medium (M)[1]	6.93	-1.20	-	-	-	-	-	-	-	-
Heavy (H)[1]	7.88	-1.04	-	-	-	-	-	-	-	-

[1]Light = 0.50 to 1.04 kg; Medium = 1.05 to 1.50 kg; Heavy = 1.51 to 2.00 kg.

Table 9.5. Non-linear regression for the effect of piglet birth weight and littermate weight on pre-weaning mortality.

Birth weight category	Intercept	Slope	SE				*P*-value			
			L vs M intercept	M vs H intercept	L vs M slope	M vs H slope	L vs M intercept	M vs H intercept	L vs M slope	M vs H slope
Light (L)[1]	-2.35	1.19	0.1406	1.488	0.702	0.935	<0.0001	0.003	0.30	0.02
Medium (M)[1]	-3.64	1.19	-	-	-	-	-	-	-	-
Heavy (H)[1]	-8.09	3.47	-	-	-	-	-	-	-	-

[1]Light = 0.50 to 1.04 kg; Medium = 1.05 to 1.50 kg; Heavy = 1.51 to 2.00 kg.

Figure 9.1. Effect of piglet birth weight category and littermate weight on predicted weaning weight.

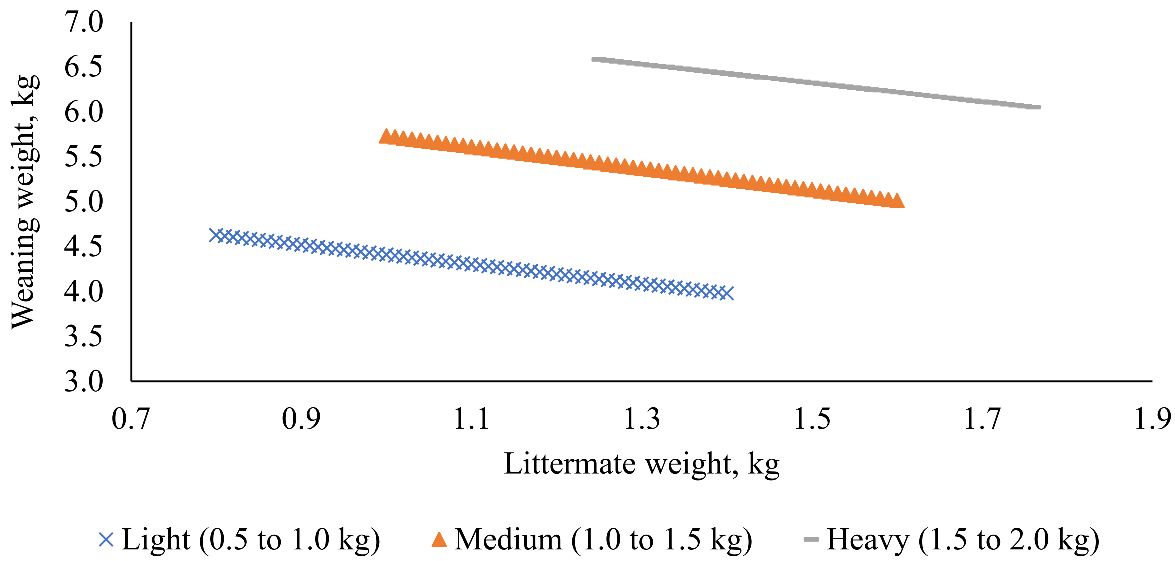
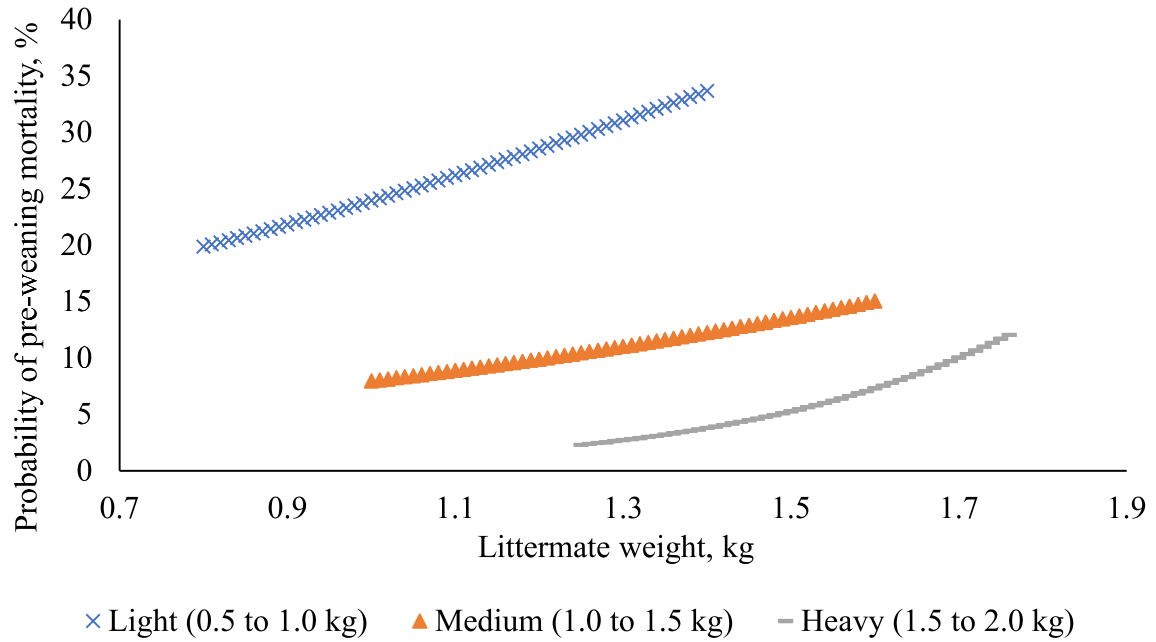


Figure 9.2. Effect of piglet birth weight category and littermate weight on predicted probability of pre-weaning mortality.



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CHAPTER 10: Effect of rearing cross-fostered piglets in litters of differing size relative to sow functional teat count on pre-weaning growth and mortality

Abstract

Litter sizes of sows in commercial production have increased significantly over the last 30 years. Cross-fostering has been commonly used to equalize either litter sizes and/or piglet birth weights within litters. However, there is limited published information on the effect of the number of piglets per litter after cross-fostering relative to sow functional teat number on piglet pre-weaning mortality (PWM) and growth. This study used a randomized complete block design; blocking factors were farrowing day and sow parity, body condition score, and functional teat number. Three Litter Size treatments were compared: Under (2 piglets less than the sow functional teat number); Equal (the same number of piglets as sow functional teat number); Over (2 piglets more than the sow functional teat number). Piglets were weighed at 24 h after birth and randomly allotted to create litters with similar average and CV of birth weight and the appropriate litter sizes for each treatment. There were 13 blocks of 3 litters (total 39 litters and 561 piglets). Weaning weights were collected at 19.5 ± 0.50 d of age; all PWM was recorded. Piglet weight data were analyzed using PROC MIXED of SAS, and PWM data were analyzed using PROC GLIMMIX of SAS as binary response data. A retrospective analysis was performed to evaluate the effects of piglet birth weight, with each piglet being classified into one of three Birth Weight Categories (BWC): Light (0.5 to 1.0 kg), Medium (1.0 to 1.5 kg), or Heavy (> 1.5 kg). There were no Litter Size by BWC interactions ($P > 0.05$) for any measurement, therefore, final models included the fixed effect of Litter Size or BWC and random effect of sow within block. The Under treatment had lower ($P \leq 0.05$) PWM than the Over treatment, with the Equal treatment being intermediate and not different ($P > 0.05$) to the others. There was also a

tendency ($P = 0.07$) for piglets in the Under treatment to have greater weaning weights compared to the other two treatments. Light piglets had lower ($P \leq 0.05$) weaning weights and higher ($P \leq 0.05$) PWM compared to the other two BWC. Heavy BWC piglets had greater ($P \leq 0.05$) weaning weights but similar ($P > 0.05$) PWM compared to Medium piglets. In conclusion, reducing litter size after cross-fostering to two piglets below the number of functional teats of the sow decreased PWM and tended to increase weaning weights.

Introduction

Pre-weaning mortality represents a major economic loss to producers and is also a significant animal welfare concern. There is evidence that levels on commercial sow farms have increased over recent years (currently averaging 10 to 15% of piglets born alive). This has been associated with the increases in litter sizes that have occurred over the same time period, with the total number of piglets born currently being 14 to 17 piglets per litter (PigChamp, 2004, 2019; SEGES, 2017; Agriculture and Horticulture Development Board, 2020). As a result, it has become increasingly common for the total number of piglets born alive within a litter to exceed the number of functional teats on the sow. Developing practical approaches to rearing this increased number of piglets is important.

Cross-fostering has been widely used in commercial production to reduce competition between piglets by equalizing litter sizes and/or reducing piglet weight variation within a litter. In practice, there are a number of potential approaches to cross-fostering that can be used. However, the studies that have been published are often of limited relevance for development of commercial protocols. While there have been several studies that reported on the effects of litter size on piglet pre-weaning growth and mortality, most previous research is relatively old and used litter sizes that are small compared to current production levels (typically ≤ 12 piglets per litter; e.g. Stewart and Diekman,1989; English and Bilkei, 2004; Deen and Bilkei, 2004). Of the studies that evaluated the effect of litter size on piglet pre-weaning growth and mortality, there are large differences in study design, making the results highly variable. Many studies used survey data collected from multiple commercial farms (e.g. Zindove, 2011; Roehe and Kalm, 2000; KilBride et al., 2012), which often have different management protocols; this results in confounding of many of the factors of interest such as average piglet birth weight. However, in general, studies found that reducing litter size also reduced piglet pre-weaning mortality and/or improved weaning weights.

In addition, few published studies have compared cross-fostered litters of differing sizes under controlled conditions, and there have been no studies that related litter size after cross-fostering to the functional teat number of the sow. It has been reported that modern commercial sows have, on average, approximately 14 functional teats and there is no evidence that this number has changed to any extent recently (Charal, 2009; Rothe, 2011; Earnhardt, 2019). With historical cross-fostering studies using litter sizes between 6 and 12 piglets, the number of functional teats was unlikely to limit teat access for piglets. However, with current litter sizes exceeding the functional teat number, there is increased competition for teat access. In order to develop optimal cross-fostering procedures, it is critical to understand the relationship between functional teat number, litter size, and piglet pre-weaning survival and growth. Therefore, the objective of this study was to compare litter sizes ranging from below to in excess of sow functional teat number using cross-fostered piglets for effects on pre-weaning growth and mortality.

Materials and Methods

This study was carried out on a commercial sow facility of The Maschhoffs, LLC, located near Beardstown, IL, USA. Protocols for this study were approved by the University of Illinois Institute of Animal Care and Use Committee prior to the start of the research.

Animals and Management

The sows used were from standard commercial crossbred lines that had been mated to commercial sire lines. Housing and management of sows and piglets were generally in line with commercial procedures and practices. The facilities used consisted of rooms with 48 individual farrowing crates and pens. Farrowing pen dimensions were 1.52 m x 2.07 m (total pen floor space of 3.15 m^2), with solid side walls and woven metal flooring. A farrowing crate was located in the center of each pen, with dimensions of 0.55 m x 1.95 m (floor space within the crate of 1.07 m^2). The thermostat in the farrowing rooms was set at 22.4°C on the day of farrowing and subsequently reduced to 18°C for the duration of the study. Room temperature was maintained using heaters, evaporative coolers, and fan ventilation as needed. Sows were moved into the farrowing facilities around d 112 of gestation. All sows within a farrowing room had been inseminated on the same day and were induced on d 114 to farrow on d 115 of gestation using 2 cc of prostaglandin F2α (given at 0600 h; Lutalyse®, Pfizer Animal Health US).

During gestation and lactation, sows were fed diets formulated to meet or exceed the nutritional requirements proposed by the National Research Council (2012). Before farrowing, sows were fed approximately 1 kg of feed twice each day (at approximately 0600 h and 1400 h). Subsequently, sows had *ad libitum* access to feed throughout lactation via a sow-operated feed dispenser attached to the feed trough. Sows and piglets had *ad libitum* access to water via nipple-type drinkers located in the sow feeding trough and farrowing pen, respectively. Standard pig processing tasks (tail docking, physical castration of males, iron and antibiotic injections) were carried out at approximately five days after birth. Sows and litters were taken off-test when piglets reached 19 or 20 d of age, depending on farrowing date.

Pre-allotment Data Collection

Sow parity, genetic line, body condition score (on a scale of 1 = extremely thin to 5 = extremely fat), and number of teats and teat functionality score (Score 1 = ideal, elongated and pointed with no visible defects; Score 2 = not ideal, not as elongated, but with no visible defects; Score 3 = non-functional, the teat was severely damaged or visibly defective) were determined on all sows two days prior to allotment. On the day after farrowing, piglets were weighed individually. Weight and gender were recorded, and each piglet was given a uniquely numbered ear tag. Piglets that were considered by the investigators to be non-viable were weighed but not used in the study.

Experimental Design, Treatments, and Allotment

The study utilized a randomized complete block design with three Litter Size treatments: Under = 2 piglets less than the sow functional teat number; Equal = the same number of piglets as the sow functional teat number; Over = 2 piglets more than the sow functional teat number. Allotments were carried out on the day after farrowing immediately after the piglets had been weighed. Each block was formed using three sows with similar parity (± 1; no parity 1 gilts were used), a similar body condition score (± 1), and the same number of functional teats (scores 1 and 2) and were each randomly allotted to one of the Litter Size treatments. All of the sows used in the study had 13, 14, or 15 functional teats, therefore, litter sizes ranged from 11 to 17 piglets, depending on block and Litter Size treatment. Sow genetic line was balanced across treatments over the entire study period. Allotment of piglets to litters was accomplished by forming outcome groups of three piglets of the same gender and similar birth weight and randomly allotting one piglet from the outcome group to each Litter Size treatment. This process was repeated until all litters in the block had two piglets more than the sow functional teat number. Subsequently, 2 and 4 piglets were removed from the Equal and Under treatments, respectively, to maintain a similar average piglet weight (± 0.05 kg) and CV (± 2.5%) of piglet weight and similar proportions of piglets of each gender (± 1) across all litters within the block. No more than three littermates were within any one litter; piglets were moved between litters as necessary to meet these allotment restrictions. Piglets weighing < 0.50 kg or considered by the investigators to be non-viable were not used.

Measurements

Litters were checked daily and all piglets were assigned a vitality score (on a scale of 1 to 4): Score 1 = Emaciated and piglet showed signs of weakness and lethargy; Score 2 = Very thin and piglet showed some signs of lethargy, but still able to nurse; Score 3 = Thin but piglet having high energy levels and normal behavior; Score 4 = Ideal with piglet having high energy levels and normal behavior. Piglets with a vitality score 1 were euthanized; those with a score of 2 were removed from the litter, placed on a non-test sow with small piglets, and recorded as a mortality; those with a score of 3 were treated according to farm protocol but remained on-test; those with a score 4 were not treated and remained on-test. All piglets removed during the study period due to low vitality score or death were considered as pre-weaning mortalities (PWM). If a piglet was removed from the study due to PWM, the date, tag number, vitality score, weight, and cause of PWM were recorded. Necropsies were performed on all piglets that died to determine cause of death. Piglets were weighed again at the end of the test period (weaning weight; 19 or 20 d of age), and average daily gain was calculated.

Statistical Analysis

All data were analyzed using SAS v. 9.4 (SAS Inst. Inc., Cary, NC). This study utilized a randomized complete block design with 13 replicates/blocks, for a total of 39 sows/litters and 561 piglets. Blocks consisted of three sows/litters, one litter of each Litter Size treatment. The PROC UNIVARIATE procedure of SAS was used to verify normality and homogeneity of variances of the residuals. All variables that conformed to the assumptions of normality and homogeneity (directly or through transformation of the data) were analyzed using the PROC MIXED procedure of SAS (Littell et al., 1996). Individual piglet weight data, average daily gain, and average age of piglets at mortality were analyzed with PROC MIXED and PWM data were analyzed as a binary response with PROC GLIMMIX. Models included the fixed effects of Litter Size treatment and the random effects of sow within block. In addition, a retrospective analysis was carried out to evaluate the effects of piglet birth weight on all parameters by assigning each piglet to a Birth Weight Category (BWC): Light = 0.5 to 1.0 kg; Medium = 1.0 to 1.5 kg; Heavy = > 1.5 kg. There were no interactions (P > 0.05) between BWC and Litter Size for any of the measurements, therefore models for the effect of BWC included only this fixed effect and the random effect of sow within block. Least-squares means for the effects of Litter Size or BWC were separated using the PDIFF option of SAS, being considered different at $P \leq 0.05$.

Regression analyses were carried out to determine the effect of Litter Size and piglet birth weight on weaning weight and PWM, and to estimate the effect of Litter Size on the relationship between day of the study period and the average number of piglets per litter. For weaning weight and the number of piglets per litter, PROC REG of SAS was used, and for the binary response of pre-weaning mortality, PROC Logistic of SAS was used. Independent variables for the analysis of piglet weaning weight included Litter Size treatment (as categorical variables), piglet birth weight as a linear and quadratic term, and all interactions. Independent variables for the analysis of the number of piglets per litter included Litter Size treatment (as categorical variables), day, and the interactions. Independent variables for the analysis of pre-weaning mortality included Litter Size treatment (as categorical variables), piglet birth weight as a linear term, and all interactions.

Results and Discussion

A summary of sow parameters for each of the Litter Size treatments are presented in Table 10.1. In general, the parity and body condition scores of sows used on each treatment were similar, and were typical of those reported in contemporary studies carried out with commercial populations (Maes et al., 2004; Vande Pol et al., 2020a,b). Few studies have reported on sow teat number and functionality, however, recent studies that evaluated these parameters found similar results to the current study. Kim et al. (2005) reported that the average number of teats for Landrace and Yorkshire gilts were 14.9 and 13.7, respectively. Similarly, Vande Pol et al. (2020a,b) reported an average total number of teats between 14.4 and 14.7. Both studies also utilized the same functionality scores as the current study, and found that 78.5, 21.5, and 2.8% of the total number of teats had functionality scores of 1, 2, and 3, respectively for Vande Pol et al. (2020a); these were 84.3, 13.8, and 2.0%, respectively for Vande Pol et al. (2020b). Balzani et al. (2016) reported that 82% of teats were scored as perfectly functional, 16% as partially functional, and 0.2% as completely non-functional. All of these results are similar to those of the current study, which found that the percentage of the total number of teats with functionality scores of 1, 2, and 3 were 82.9, 15.7, and 2.1%, respectively. The total number of functional teats for the current study, which averaged approximately 14, is similar to the average number of piglets born alive per sow in the U.S. (PigChamp, 2019). This indicates that litter sizes used in this study are representative of those of the U.S. industry, and suggests that the results of this study are commercially relevant.

Effects of Litter Size Treatment

The least-squares means for the effect of Litter Size treatments on piglet pre-weaning growth, PWM, and the causes and timing of PWM are presented in Table 10.2. By design, the number of piglets per litter after cross-fostering was lowest ($P \leq 0.05$) for the Under treatment, greatest ($P \leq 0.05$) for the Over treatment, with Equal treatment being intermediate to and different ($P \leq 0.05$) from the other two treatments. At 7 d after birth, the Under treatment had a lower ($P \leq 0.05$) litter size compared to the other two treatments, which were similar ($P > 0.05$). At 14 d after birth and weaning, the Under treatment had a lower litter size ($P \leq 0.05$) than the Over treatment, and the Equal treatment was intermediate and not different ($P > 0.05$) to the others. Total litter weight was greater ($P \leq 0.05$) at the start of the study period for the Over treatment compared to the other two Litter Size treatments, however, there were no differences ($P > 0.05$) at weaning. There were no differences ($P > 0.05$) between Litter Size treatments for piglet birth weight, weaning weight, or average daily gain (ADG) of all piglets (including those removed for PWM) or weaned piglets. However, there were tendencies for weaning weights ($P = 0.07$) and ADG of all piglets ($P = 0.06$) to be greater for the Under compared to the other two treatments. The Under treatment also resulted in lower ($P \leq 0.05$) PWM than the Over treatment, with the Equal treatment being intermediate and not different ($P > 0.05$) from the others (Table 10.2). There were no effects ($P > 0.05$) of Litter Size on the causes or timing of PWM. The main causes of PWM were starvation and crushing, which, in combination, accounted for 92.9, 100.0, and 92.5% of all mortality within the Under, Equal, and Over treatments, respectively (Table 10.2). The average age of piglets removed during the study for PWM was between 7.9 and 8.6 d ($P > 0.05$).

Many studies have conducted retrospective analyses of commercial or university farrowing data and have shown that, similar to the current study, increases in litter size are associated with increases in piglet mortality and decreases in piglet growth pre-weaning (e.g. Roehe and Kalm, 2000; Andersen et al., 2011; KilBride et al., 2012). Interestingly, three studies also found negative effects of rearing piglets in small litters (< 6 or < 9 piglets) on pre-weaning mortality (Sharpe, 1966; Cecchinato et al., 2008; KilBride et al., 2014). However, increases in the total number of piglets born in a litter are also associated with decreasing average piglet birth weight and increasing variation in birth weights within the litter (Roehe and Kalm, 2000; Andersen et al., 2011). It has been well-established that piglets of lower birth weights have greater mortality and lower growth rates pre-weaning than their heavier littermates (e.g. Roehe and Kalm, 2000; Herpin et al., 2002; Mesa et al., 2006). Therefore, litter size and birth weight were confounded in many of these studies, and it is difficult to determine whether increases in pre-weaning mortality were due to the effects of litter size or piglet birth weight.

There have been very few controlled studies that have evaluated the effects of litter size in cross-fostered litters, or in litters with balanced piglet birth weights across treatments. Of the studies that utilized controlled litter size treatments, most found that reduced litter sizes increased growth and/or decreased pre-weaning mortality, similar to the current study (Stewart and Diekman, 1989; Auldist et al., 1998). Two studies (English and Bilkei, 2004; Deen and Bilkei, 2004) found that light birth weight piglets (0.9 to 1.0 kg), had similar mortality in small (6 piglets) or large litters (12 piglets) when reared with other light piglets, but had greater mortality in large litters when reared with heavy (> 1.6 kg) littermates. This indicates a reduced ability of light piglets to compete for teat access when reared with heavy littermates. Similarly, Milligan et al. (2002) found that pre-weaning survival and weaning weights were greater in smaller litters (< 11 piglets) for low birth weight piglets, but the effects of litter size were minimal for heavier piglets. However, due to the cross-fostering protocol, average piglet birth weight was lower for larger litters, making it difficult to separate the effects of birth weight and litter size. While the results of these studies are generally similar to those of the current one, comparison is difficult as they did not use litter sizes above 14 piglets, and did not relate litter size to sow functional teat number.

Only one other study was found that utilized cross-fostering to form a litter size treatment relative to sow functional teat number. Kobek-Kjeldager et al. (2020) evaluated the performance of piglets in litter sizes equal to teat count (approximately 14 piglets) compared to larger litters at a fixed size of 17 piglets, and found that pre-weaning mortality was 13.5 percentage units higher for larger litters, and piglet weight at weaning (at 28 d of age) was greater in smaller litters. The smaller litter size in the study of Kobek-Kjeldager et al. (2020) was similar to the Equal treatment of the current study, and the larger litter size was approximately one piglet larger than the Over treatment of the current study. The difference in pre-weaning mortality for the Equal and Over treatments was 6.4 percentage units in the current study, which was likely lower than that of Kobek-Kjeldager et al. (2020) due to the difference in the large litter size. The study of Kobek-Kjeldager et al. (2020) was the only one found that used litter sizes that were relevant to the increased productivity of modern commercial sows (i.e. > 14 piglets).

A regression analysis was carried out to determine the relationship between day of the study period and the number of piglets per litter for each Litter Size treatment. These results are presented in Table 10.3, and the means and standard deviations for each treatment on each day are illustrated in Figure 10.1. The regression coefficients were estimated for the Under treatment, and adjustments to these were estimated for the other two Litter Size treatments. Within the Under treatment, there was a linear effect of day ($P \leq 0.05$) on the number of piglets per litter, with a decrease of 0.05 piglets per day. Both the Equal and Over treatments had positive ($P \leq 0.05$) intercept adjustments, indicating the differences in litter sizes at the start of the study. However, the slope adjustments were negative ($P \leq 0.05$), indicating that the number of piglets per litter decreased at greater rates for these two treatments (Figure 10.1). This finding is similar to the results for PWM, however, this allows for some prediction of weaned litter size based on an individual sows litter size after cross-fostering, relative to the number of functional teats. These regression relationships suggest that the addition of four piglets (for the Over treatment) to the Under litter size resulted in a total of approximately two of these four additional piglets, and the addition of two piglets (for the Equal treatment), resulted in a total loss of approximately one of these two additional piglets. This suggests that for each 2-piglet increase in litter size, only about half of those will survive to weaning.

Effects of Birth Weight Category

The effects of BWC on piglet pre-weaning growth, PWM, and timing and causes of PWM are presented in Table 10.4. By design, Light piglets had the lowest ($P \leq 0.05$) birth weights, with Heavy piglets had the greatest ($P \leq 0.05$), and Medium piglets were intermediate and different ($P \leq 0.05$) to the other two BWC. Similarly, Light piglets had lower ($P \leq 0.05$) weaning weights and ADG (for all piglets and weaned piglets) compared to Heavy piglets, and Medium piglets were intermediate and different to ($P \leq 0.05$) the other two BWC. Light piglets also had greater ($P \leq 0.05$) PWM than the other two BWC, which were similar ($P > 0.05$; Table 10.4). There was no effect ($P > 0.05$) of BWC on any of the causes or timing of piglet PWM.

The main causes of PWM were starvation and crushing, which, in combination, accounted for 100, 93.5, and 90.9% of all mortality within Light, Medium, and Heavy BWC, respectively (Table 10.4).

The effects of Birth Weight Category on weaning weight, average daily gain, and pre-weaning mortality found in the current study were not surprising, as many studies have found that heavier birth weights are strongly correlated with increased weaning weight and reduced pre-weaning mortality (e.g. Roehe and Kalm, 2000; Herpin et al., 2002; Mesa et al., 2006). Two other studies by Vande Pol et al. (2020a,b) were carried out on the same farm as the current one and using the same personnel, and reported effects of piglet birth weight on the causes and timing of pre-weaning mortality. Vande Pol et al. (2020a) found that Heavy (1.5 to 2.0 kg) piglets had greater ages of mortality than Light (0.5 to 1.0 kg) or Medium (1.0 to 1.5 kg) piglets, and that Medium piglets had a greater percentage of mortality due to crushing than the other two Birth Weight Categories. These results are in contrast to the study of Vande Pol et al. (2020b), which found that Heavy (1.5 to 2.0 kg) piglets had a greater percentage of mortality due to starvation, and that Medium (1.0 to 1.5 kg) piglets had the highest average age of mortality. Both of these studies findings differ from the those of the current study, which found no effect of BWC on these parameters, however, this study had fewer replications, and may not have been large enough to detect these differences.

Regression Analyses

The results described above (Tables 10.2 and 10.4) suggested that there were effects of both Litter Size treatment and piglet birth weight on weaning weight and PWM. Consequently, regression analyses were conducted to determine the relationship between piglet birth weight and weaning weight for each Litter Size treatment, and these are presented in Table 10.5, and illustrated in Figure 10.2. The regression coefficients were estimated for the Under treatment, and adjustments to these coefficients were determined for the Equal and Over treatments. There were linear and quadratic effects ($P \leq 0.05$; Table 10.5) of piglet birth weight on weaning weight for the Under treatment. The intercept adjustments for the Equal and Over treatments were both less than 0 ($P \leq 0.05$), however, they were similar in magnitude ($P > 0.05$). The linear and quadratic coefficient adjustments for the Equal and Over treatments were not different to 0 ($P > 0.05$). These results indicate that the intercepts for these two treatments were lower than that of the Under treatment, however, the curves were similar for the three treatments (Figure 10.2).

The results of the analysis for PWM are presented in Table 10.6, and illustrated as the probability of PWM in Figure 10.3. Similar to above, the regression coefficients were estimated for the Under treatment, and adjustments to these coefficients were determined for the Equal and Over treatments. The relationship between piglet birth weight and the log odds of PWM was not quadratic ($P > 0.05$), therefore, only the linear terms were included in the model. Within the Under treatment, there was a linear effect of piglet birth weight ($P \leq 0.05$) on the log odds of PWM, with each 1 kg increase in piglet birth weight decreasing the log odds by 1.74 (Table 10.6). The intercept adjustment for the Over treatment was greater ($P \leq 0.05$) than 0, however the intercept adjustment for the Equal treatment was not different to 0 ($P > 0.05$; Table 10.6). The linear coefficient adjustments for the Equal and Over treatments were not different to 0 ($P > 0.05$). These results indicate that the intercept for the Over treatment was lower than that of the other two treatments, however, the lines were similar for all three treatments (Table 10.6).

The log odds of PWM were estimated for each treatment and all values of piglet birth weight, and the predicted probability of PWM was calculated by taking the exponent of these values, and converting using the formula: predicted probability of PWM = odds/(1+odds). The relationship between these calculated probabilities and piglet birth weight were plotted for each treatment (Figure 10.3). The predicted probability of PWM increased with decreasing piglet birth weight for all Litter Size treatments. As birth weight decreased from 2.3 to 0.7 kg, the predicted probability of PWM increased by 21.4, 35.9, and 47.5% for the Under, Equal, and Over treatments, respectively (Figure 10.3).

For weaning weight, the Under treatment resulted in greater weaning weights for piglets of all birth weights compared to the other two treatments. However, these differences were relatively small. In contrast, for PWM, as the Litter Size treatment resulted in differences in the intercepts of the log odds regressions, the effect was essentially multiplying the probability of mortality by a similar constant for all birth weights. What this means is that the probability of PWM was approximately doubled for the Over compared to the Under treatment for all birth weights. Since lower birth weight piglets already have a higher probability of PWM, doubling this means that the increased PWM of the Over treatment was largely at the expense of these low birth weight piglets as compared to their heavier littermates. For example, the predicted PWM of a 1.0 kg piglet would be 15.5% on the Under treatment and 34.0% on the Over treatment, whereas for a 2.0 kg piglet these would be 3.1 and 6.1%, respectively. Biologically, this makes sense, as larger piglets are more competitive for teat access, and reducing litter size would make more teats available for lighter piglets to nurse sufficiently for survival.

Light (< 1.0 kg) piglets represented approximately 11% of the population used in the study, compared to 42% having Medium birth weights (1.0 to 1.5 kg), and 47% having Heavy (> 1.5 kg) birth weights, with distributions being similar across treatments. With a greater mortality rate of Light piglets on the Over compared to the Under treatment, the average birth weight of surviving piglets was greater for the Over treatment, however, the average weaning weights were still lower. This indicates that the birth weight distribution of weaned piglets would tend to be heavier for the Over treatment. With heavier piglets having a greater pre-weaning growth potential, the negative effects of the larger litter size on piglet weaning weight may be greater than they initially appear.

Overall, the results of this study show that increasing litter size above sow functional teat number is detrimental for piglet pre-weaning survival, and that reducing litter size below functional teat number improves pre-weaning survival and, to a lesser extent, piglet growth. Selection of the optimum litter size to use after cross-fostering for commercial production may vary depending on the specific situation, as many other management factors are involved in these decisions. For example, comparing the cost of increasing the number of nurse sows to reduce litter size with the benefit of increased piglet productivity, or the benefit of increasing litter size in order to wean sows early for re-breeding at the expense of reduced piglet performance. However, the results of this study provide relationships that can be used as a basis for these decisions, and strongly suggest that sow functional teat number is an important factor that should be considered in the development of cross-fostering protocols.

Tables and Figures

Table 10.1. Summary of sow characteristics by litter size treatment.

	Litter Size[1]				
Item.	Under	Equal	Over	SEM	*P*-value
Total number of sows	13	13	13	-	-
Average sow parity[2]	3.9	2.7	3.0	0.51	0.22
Number of sows by parity[2]					
Parity 2	1	3	3	-	-
Parity 3	4	6	4	-	-
Parity 4 and 5	2	2	5	-	-
Parity 6 and 7	6	2	1	-	-
Average sow body condition score[3]	3.38	3.77	3.69	0.151	0.18
Number of sows by body condition score[3]					
1.0 to 1.5	0	0	0	-	-
2.0 to 2.5	1	0	1	-	-
3.0 to 3.5	9	7	6	-	-
4.0 to 4.5	3	5	5	-	-
5	0	1	1	-	-
Average number of teats[4]					
Score 1	11.9	12.0	11.5	0.46	0.43
Score 2	2.1	2.1	2.5	0.55	0.46
Score 3	0.5	0.2	0.2	0.31	0.59
Functional teats (Score 1+2)	14.2	14.2	14.3	0.34	0.94

[1]Under = 2 piglets less than the sow functional teat number; Equal = the same number of piglets as the sow functional teat number; Over = 2 piglets more than the sow functional teat number.

[2]Parity = total number of litters including the one used in the study.

[3]On a scale of 1 extremely thin to 5 extremely fat.

[4]On a scale of 1 to 3: Score 1 = ideal, elongated and pointed with no visible defects; Score 2 = not ideal, teat end less elongated, but no visible defects; Score 3 = non-functional, teat severely damaged or visibly defective

Table 10.2. Least-squares means for the effects of litter size treatment on piglet weight, average daily gain, pre-weaning mortality, and the causes and timing of mortality, as a percentage of total mortality within litter size treatment.

	Litter Size[1]				
Item.	Under	Equal	Over	SEM	*P*-value
Number of piglets	161	187	213	-	-
Litter size					
After cross-fostering	12.1^{c}	14.1^{b}	16.1^{a}	0.30	<0.0001
At 7 d after birth	11.8^{b}	13.4^{a}	14.6^{a}	0.81	<0.0001
At 14 d after birth	11.7^{b}	12.8^{ab}	13.8^{a}	0.44	0.01
At weaning	11.3^{b}	12.6^{ab}	13.3^{a}	0.51	0.03
Litter weight, kg					
Birth	16.1^{b}	19.0^{b}	22.0^{a}	1.41	0.0001
Weaning	69.8	73.8	78.0	10.09	0.41
Piglet weight, kg					
Birth	1.46	1.46	1.46	0.058	0.97
Weaning	6.17	5.86	5.84	0.184	0.07
Average daily gain, kg					
Weaned piglets	0.243	0.225	0.223	0.0083	0.20
All piglets[2]	0.227	0.200	0.190	-	0.06
Pre-weaning mortality, %	7.69^{b}	11.5^{ab}	17.9^{a}	-	0.04
Number of mortalities	14	23	40	-	-
Cause of mortality, % of total					
Crushed	64.3	47.8	47.5	-	0.56
Starvation	28.6	52.2	45.0	-	0.52
Other	7.1	0.0	7.5	-	0.99
Time of mortality, % of total					
Day 1 to 2	14.3	8.7	5.0	-	0.55
Day 1 to 7	50.0	52.2	55.0	-	0.94
Day 8 to weaning	50.0	47.8	45.0	-	0.94
Age of mortality, days	8.6	7.9	8.0	1.50	0.96

[a,b,c]Means with differing superscripts differ at $P \leq 0.05$.

[1]Under = 2 piglets less than the sow functional teat number; Equal = the same number of piglets as the sow functional teat number; Over = 2 piglets more than the sow functional teat number.

[2]Transformed data using a square transformation to correct for normality and homogeneity of variance of the residuals.

Table 10.3. Regression of litter size treatment on litter size by day over the study period.

Item.[1]	Coefficient	SE	*P*-value
Intercept for Under	12.21	0.077	<0.0001
Intercept adjustment for Equal	1.94	0.118	<0.0001
Intercept adjustment for Over	3.80	0.118	<0.0001
Day slope for Under	-0.05	0.007	<0.0001
Day slope adjustment for Equal	-0.04	0.010	<0.0001
Day slope adjustment for Over	-0.11	0.010	<0.0001

[1]Under = 2 piglets less than the sow functional teat number; Equal = the same number of piglets as the sow functional teat number; Over = 2 piglets more than the sow functional teat number.

Table 10.4. Least-squares means for the effects of birth weight category on piglet weight, average daily gain, pre-weaning mortality, and the causes and timing of mortality, as a percentage of total mortality within birth weight category.

	Birth Weight Category[1]				
Item.	Light	Medium	Heavy	SEM	*P*-value
Number of piglets	61	238	262	-	-
Piglet weight, kg					
Birth	0.90^{c}	1.27^{b}	1.76^{a}	0.016	<0.0001
Weaning	3.99^{c}	5.38^{b}	6.76^{a}	0.145	<0.0001
Average daily gain, kg					
Weaned piglets	0.159^{c}	0.211^{b}	0.258^{a}	0.0073	<0.0001
All piglets[2]	0.105^{c}	0.193^{b}	0.237^{a}	-	<0.0001
Pre-weaning mortality, %	37.7^{a}	11.8^{b}	7.5^{b}	-	<0.0001
Number of mortalities	24	31	22	-	-
Cause of mortality, % of total					
Crushed	37.5	54.8	54.5	-	0.40
Starvation	62.5	38.7	36.4	-	0.15
Other	0.0	6.5	9.1	-	0.94
Time of mortality, % of total					
Day 1 to 2	0.0	9.7	13.6	-	0.91
Day 1 to 7	66.7	51.6	40.9	-	0.23
Day 8 to weaning	33.3	48.4	59.1	-	0.23
Age of mortality, days	7.0	8.0	9.3	1.17	0.30

[a,b,c]Means with differing superscripts differ at $P \leq 0.05$.

[1]Light = birth weights between 0.5 and 1.0 kg; Medium = birth weights between 1.0 kg and 1.5 kg; Heavy = birth weights > 1.5 kg.

[2]Transformed data using a square transformation to correct for normality and homogeneity of variance of the residuals.

Table 10.5. Regression of litter size treatment and centered piglet birth weight on weaning weight.

Item.[1]	Coefficient[2]	SE	*P*-value
Intercept for Under	6.28	0.126	<0.0001
Intercept adjustment for Equal	-0.34	0.171	0.05
Intercept adjustment for Over	-0.37	0.169	0.03
Birth weight slope for Under	2.90	0.284	<0.0001
Birth weight slope adjustment for Equal	-0.30	0.395	0.45
Birth weight slope adjustment for Over	-0.39	0.391	0.33
Squared birth weight slope for Under	-1.20	0.355	0.001
Squared birth weight slope adjustment for Equal	-0.01	0.911	0.99
Squared birth weight slope adjustment for Over	-0.06	0.903	0.95

[1]Under = 2 piglets less than the sow functional teat number; Equal = the same number of piglets as the sow functional teat number; Over = 2 piglets more than the sow functional teat number.
[2]Using centered birth weight, with a mean of 1.46 kg.

Table 10.6. Regression of litter size treatment and piglet birth weight on the log odds of pre-weaning mortality.

Item.[1]	Coefficient	SE	*P*-value
Intercept for Under	-2.50	0.318	<0.0001
Intercept adjustment for Equal	0.31	0.417	0.46
Intercept adjustment for Over	0.88	0.376	0.02
Birth weight slope for Under	-1.74	0.865	0.04
Birth weight slope adjustment for Equal	-0.48	1.136	0.67
Birth weight slope adjustment for Over	-0.33	1.037	0.75

[1]Under = 2 piglets less than the sow functional teat number; Equal = the same number of piglets as the sow functional teat number; Over = 2 piglets more than the sow functional teat number.

Figure 10.1. Mean litter size by treatment over the study period.

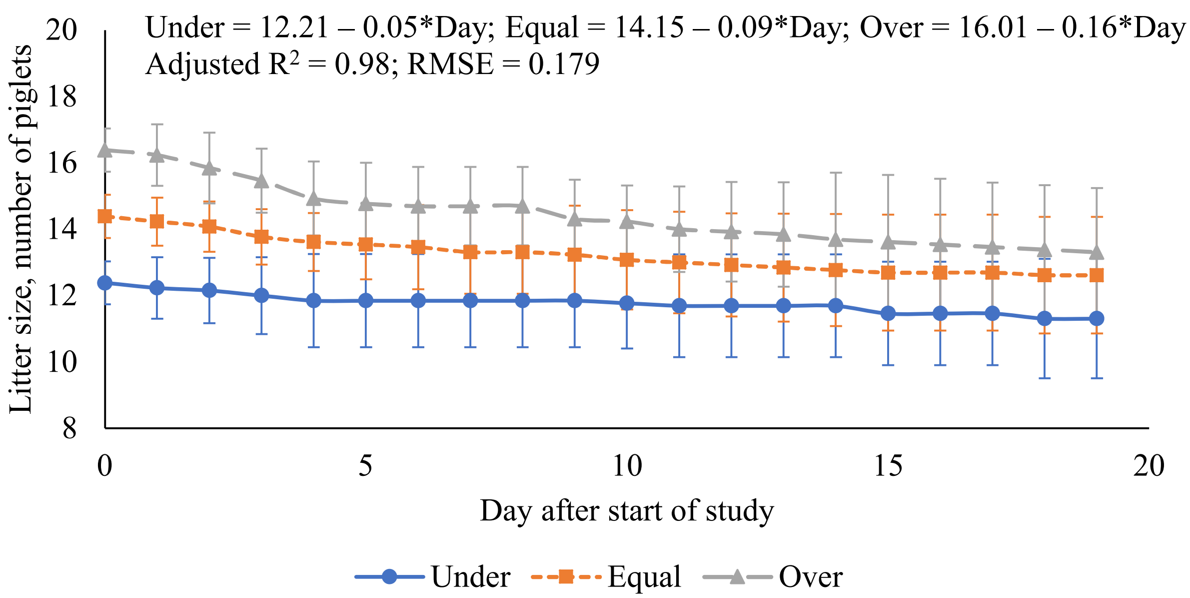


Figure 10.2. Regression lines for the effect of piglet birth weight on predicted weaning weight, within treatment.

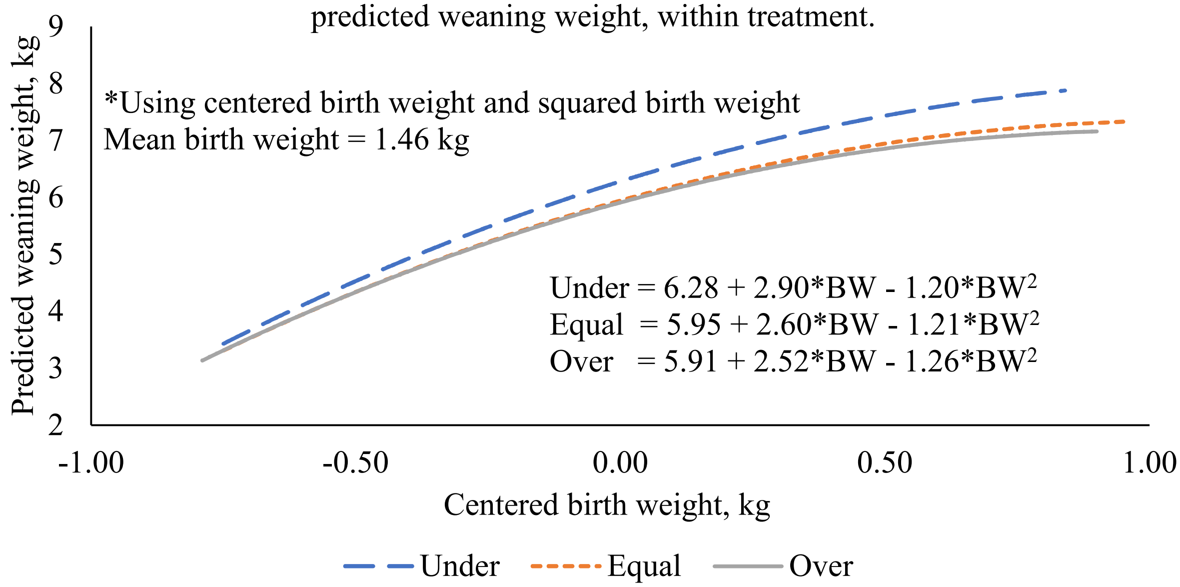
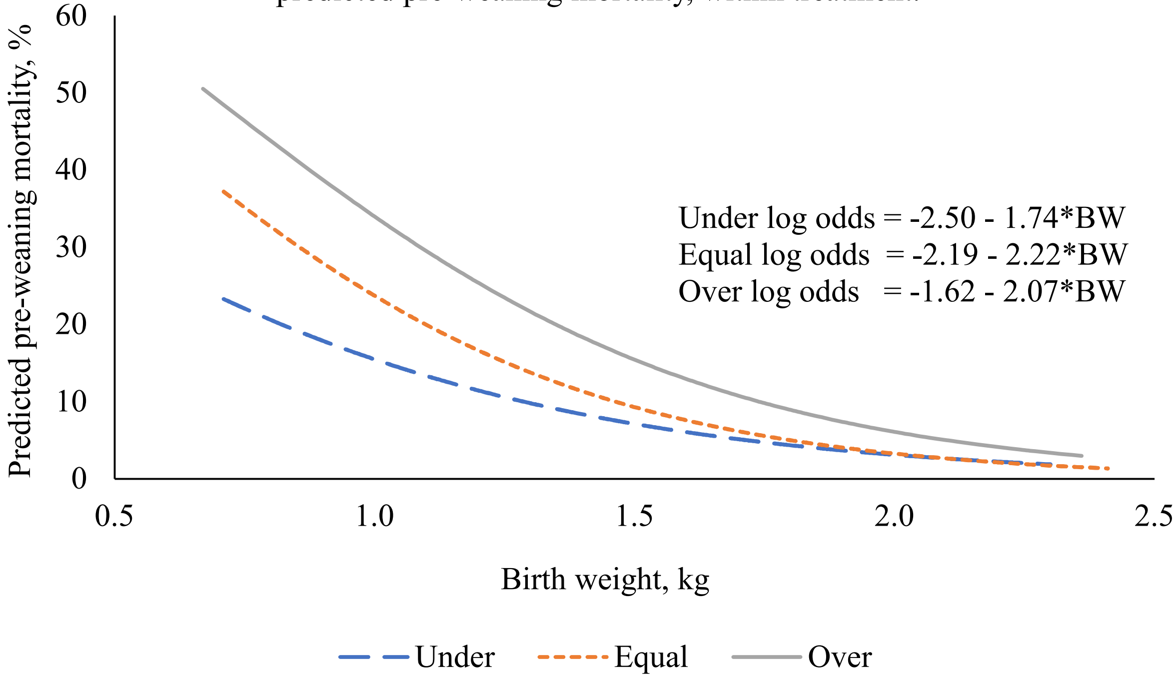


Figure 10.3. Regression lines for the effect of piglet birth weight on predicted pre-weaning mortality, within treatment.



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CHAPTER 11: Effect of number of litters used in cross-fostering on piglet pre-weaning growth and mortality

Abstract

While cross-fostering is commonly used in the commercial swine industry to equalize litter sizes and/or piglet birth weights within litters, there is limited published information for defining optimum protocols. Litter sizes in commercial pig production have increased significantly over recent decades, making understanding cross-fostering of increasing importance. This study evaluated the effects of the number of litters used in cross-fostering on pre-weaning mortality (PWM) and growth. A randomized complete block design was used to compare five treatments: 0%, 1 source (all piglets remaining on their sow of origin); 100%, 1 source (all piglets from a litter moved to a different sow); 100%, 6+ sources (piglets from at least 6 sows used to form a litter on a new sow); 50%, 2 sources (7 piglets remaining with their sow of origin and 7 from one other sow); 50%, 4+ sources (7 piglets remaining with their sow of origin and the other 7 from at least 3 other sows). Blocking factors were farrowing day and sow parity, body condition score, and functional teat number, and the average and CV of piglet birth weight. Allotments were carried out at 24 h after birth, when piglets were weighed. All litters were composed of 14 piglets. Two litters were selected for the single-source treatments; those with > 14 piglets at birth had excess piglets removed. For the other treatments, individual piglets were randomly selected such that sow and piglet blocking factors were met. There were 26 blocks of 5 litters (total 130 litters and 1820 piglets). Weaning weights were collected at 19.5 ± 0.50 d of age; all PWM was recorded. Individual piglet weight data were analyzed using PROC MIXED of SAS. Individual piglet PWM data were analyzed using PROC GLIMMIX of SAS as binary response data. Models included the fixed effect of treatment and the random effect of sow

within block. There was no effect ($P > 0.05$) of treatment on weaning weights or pre-weaning ADG of piglets. However, PWM was greatest ($P \leq 0.05$) for the 0%, 1 source (13.4%) compared to the 50%, 2 source treatment (6.3%), with the other treatments being intermediate and not always statistically different. In conclusion, cross-fostering and/or mixing litters had no effect on piglet weaning weights, but pre-weaning mortality was highest for the single-source treatments. Further research is necessary to validate these results for PWM, and to determine the biological causes of any potential differences in mortality.

Introduction

Pre-weaning mortality represents a major economic loss to producers and is a significant animal welfare concern. In addition, levels on commercial sow farms have increased over recent years, currently averaging 10 to 15% of piglets born alive, and are potentially associated with the increases in litter sizes that have occurred over the same time period (PigChamp, 2004, 2019; SEGES, 2017; Agriculture and Horticulture Development Board, 2020). With the total number of piglets born currently averaging 15 to 17 piglets per litter (SEGES, 2017; PigChamp, 2019), the number of piglets born alive often exceeds the total number of functional teats of the sow. Approaches to rearing this increased number of piglets are of great importance. One approach that is commonly used is to cross-foster piglets (moving a piglet from its birth sow to another sow during lactation) in order to match the number of piglets within a litter to the number of functional teats on the sow, and/or equalize litter size within a group of sows. There is limited understanding of the effect of cross-fostering *per se*, and previous research often confounds other factors such as piglet birth weight or litter size. In particular, there has been little to no research to evaluate important factors such as the number of source litters used to create a cross-fostered litter. Forming litters from multiple sources could increase disease challenges, which may counteract any benefits derived from cross-fostering *per se*.

Of the studies that have evaluated the effects of piglet cross-fostering, the methodology used was highly variable in terms of the timing of cross-fostering during lactation, litter sizes after cross-fostering, and the number or proportions of piglets cross-fostered within a litter. This variation in methodology makes comparison across studies difficult, and has likely contributed to the variability in reported results. Several studies have found no effect of cross-fostering on piglet pre-weaning growth or mortality (Bishop, 2011; Heim et al. 2012), whereas others have showed reduced pre-weaning performance for cross-fostered piglets (Horrell and Bennett, 1981; Stewart and Diekman, 1989; Giroux et al., 2000; KilBride et al., 2014). In order to develop optimal cross-fostering procedures, it is critical to understand the effects of cross-fostering, as well as the effects of mixing piglets of differing origins on piglet pre-weaning survival and growth. Therefore, the objective of this study was to determine the effects of cross-fostering with or without mixing piglets from multiple source litters on pre-weaning mortality and growth.

Materials and Methods

This study was carried out on a commercial sow facility of The Maschhoffs, LLC, located near Beardstown, IL, USA. Protocols for this study were approved by the University of Illinois Institute of Animal Care and Use Committee prior to the start of the research.

Animals and Management

The sows used were from standard commercial crossbred lines that had been mated to commercial sire lines. Housing and management of sows and piglets were generally in line with commercial procedures and practices. The facilities used consisted of rooms with 48 individual farrowing crates and pens. Farrowing pen dimensions were 1.52 m x 2.07 m (total pen floor space of 3.15 m^2), with solid side walls and woven metal flooring. A farrowing crate was located in the center of each pen, with dimensions of 0.55 m x 1.95 m (floor space within the crate of 1.07 m^2). The thermostat in the farrowing rooms was set at 22.4°C on the day of farrowing and subsequently reduced to 18°C for the duration of the study. Room temperature was maintained using heaters, evaporative coolers, and fan ventilation as needed. Sows were moved into the farrowing facilities around d 112 of gestation. All sows within a farrowing room had been inseminated on the same day and were induced on d 114 to farrow on d 115 of gestation using 2 cc of prostaglandin F2α (given at 0600 h; Lutalyse®, Pfizer Animal Health US).

During gestation and lactation, sows were fed diets formulated to meet or exceed the nutritional requirements proposed by the National Research Council (2012). Before farrowing, sows were fed approximately 1 kg of feed twice each day (at approximately 0600 h and 1400 h). Subsequently, sows had *ad libitum* access to feed throughout lactation via a sow-operated feed dispenser attached to the feed trough. Sows and piglets had *ad libitum* access to water via nipple-type drinkers located in the sow feeding trough and farrowing pen, respectively. Standard pig processing tasks (tail docking, physical castration of males, iron and antibiotic injections) were carried out at approximately five days after birth. Sows and litters were taken off-test when piglets reached 19 or 20 d of age, depending on farrowing date.

Pre-allotment Data Collection

Sow parity, genetic line, body condition score (on a scale of 1 = extremely thin to 5 = extremely fat), and number of teats and teat functionality score (Score 1 = ideal, elongated and pointed with no visible defects; Score 2 = not ideal, not as elongated, but with no visible defects; Score 3 = non-functional, the teat was severely damaged or visibly defective) were determined on all sows on the day before farrowing. On the day after farrowing, piglets were individually weighed, gender was recorded, and each piglet was given a uniquely numbered ear tag. Piglets that were considered by the investigators to be non-viable were weighed but not used in the study.

Experimental Design, Treatments, and Allotment

The study utilized a randomized complete block design with five treatments: 0%, 1 source (14 piglets remaining on their sow of origin); 100%, 1 source (14 piglets from a litter moved to a different sow); 100%, 6+ sources (14 piglets from at least 6 sows used to form a litter on a new sow); 50%, 2 sources (7 piglets remaining with their sow of origin and 7 from one other sow); 50%, 4+ sources (7 piglets remaining with their sow of origin and the other 7 from at least 3 other sows). Allotments were carried out on the day after farrowing immediately after the piglets had been weighed. Piglets weighing < 0.50 kg or considered by the investigators to be non-viable were not used. Each block was formed using five sows with similar parity (± 1; no parity 1 gilts were used), a similar body condition score (± 1), and the same number of functional teats (scores 1 and 2). Sow genetic line was balanced across treatments over the entire study period. No more than three littermates were allotted within the groups of cross-fostered piglets on the 100%, 6+ sources and 50%, 4+ sources treatments. All of the litters consisted of 14 piglets with similar mean birth weight (± 0.05 kg) and coefficient of variation (CV; ± 2.5 %) of birth weight and similar gender ratios.

These piglet blocking criteria were accomplished by removing piglets (for both 1-source treatments if the sow had > 14 piglets) or selecting piglets (for the other three treatments). The groups of seven littermates remaining together for the 50% cross-fostered treatments were selected to have a similar mean and CV of birth weight as the non-fostered piglets on the 1-source treatments. The piglets used to create the multiple source treatments (in the 100%, 6+ sources and

50%, 4+ sources treatments) were selected to have similar average and CV of birth weight, and similar gender ratios as the 1-source litters.

Measurements

Piglets were weighed again at the end of the test period (weaning weight; 19 or 20 d of age), and average daily gain was calculated. If a piglet was removed from the study due to pre-weaning mortality (PWM), the date, tag number, weight, and cause of PWM were recorded. Necropsies were performed on all piglets that died to determine cause of death. Litters were checked daily and all piglets were assigned a vitality score (on a scale of 1 to 4): Score 1 = Emaciated and piglet showed signs of weakness and lethargy; Score 2 = Very thin and piglet showed some signs of lethargy, but still able to nurse; Score 3 = Thin but piglet having high energy levels and normal behavior; Score 4 = Ideal with piglet having high energy levels and normal behavior. Piglets with a vitality score 1 were euthanized; those with a score of 2 were removed from the litter, placed on a non-test sow with small piglets, and recorded as a morbidity; those with a score of 3 were treated according to farm protocol but remained on-test; those with a score 4 were not treated and remained on-test. All piglets removed during the study period due to low vitality score or death were considered as PWM.

Statistical Analysis

All data were analyzed using SAS v. 9.4 (SAS Inst. Inc., Cary, NC). This study utilized a randomized complete block design with 26 replicates/blocks, for a total of 130 sows/litters and 1820 piglets. Blocks consisted of five sows/litters, with one litter of each cross-fostering treatment. Any litters for which the sow was replaced during the study period (due to poor lactation or disease) were removed from the data set prior to analysis. The PROC UNIVARIATE procedure of SAS was used to verify normality and homogeneity of variances of the residuals. Individual piglet weight data, average daily gain, and average mortality age conformed to the assumptions of normality and homogeneity (directly or through transformation of the data) and were analyzed using the PROC MIXED procedure of SAS (Littell et al., 1996). Pre-weaning mortality data were analyzed as a binary response with PROC GLIMMIX. Models included the fixed effect of treatment and the random effects of sow within block. Least-squares means for the effects of treatment were separated using the PDIFF option of SAS, being considered different at $P \leq 0.05$.

Results and Discussion

A summary of sow parameters for each of the cross-fostering treatments are presented in Table 11.1. There were no differences ($P > 0.05$) between treatments for any of these parameters, with the exception of the number of teats with a score of 3 (non-functional), which was not expected to have any impact on piglet performance. In general, the sows used in this study were typical of those in contemporary commercial production. Sow body condition scores for the current study were between 3.6 and 3.9 (Table 11.1), which is within the range reported in previous studies that used the same scoring scale. For example, Vande Pol et al. (2020a,b,c) found body condition scores at farrowing of between 3.4 and 3.9. Maes et al. (2004) reported an average body condition score of commercial sows at farrowing of 3.2.

Kim et al. (2005) reported that the average number of teats for Landrace and Yorkshire gilts were 14.9 and 13.7, respectively. This is similar to the total number of teats found in the current study (between 14.6 and 14.9; Table 11.1), and those of Vande Pol et al. (2020a,b,c; between 14.4 and 14.7). In the current study, the percentage of the total number of teats with functionality scores of 1, 2, and 3 were 84.1, 14.3, and 1.6%, respectively, which is similar to the results of previous studies that used the same scores. For example, Vande Pol et al. (2020a,b,c) found that the percentage of the total number of teats with functionality scores of 1 were between

78.5 and 84.3%, with a score of 2 were between 13.8 and 21.5%, and those with a score of 3 were between 2.0 and 2.8% of the total number of teats. Similarly, Balzani et al. (2016) scored 71.8% of teats as perfectly functional, 23.4% as partially functional, and 4.9% as completely non-functional.

The least-squares means for the effect of cross-fostering treatments on litter size, piglet pre-weaning growth, PWM, and the causes and timing of PWM are presented in Table 11.2. By design, all litters consisted of 14 piglets at the start of the study, after cross-fostering ($P > 0.05$). At 7 d after birth, litter size was greatest ($P \leq 0.05$) for the 50%, 2 source and 100%, 6+ sources treatments, lowest ($P \leq 0.05$) for the 0%, 1 source treatment, and intermediate ($P > 0.05$) for the other treatments. At 14 d after birth, litter sizes were not different between treatments, but tended ($P = 0.06$) to be lower for the 0%, 1 source treatment than the other treatments. At weaning, litter size was lowest ($P \leq 0.05$) for the 0%, 1 source treatment, highest ($P \leq 0.05$) for the 50%, 2 source treatment, and intermediate ($P > 0.05$) for the other treatments. There were no differences ($P > 0.05$) between treatments for piglet birth or weaning weight, or average daily gain. Pre-weaning mortality was higher ($P \leq 0.05$) for the 0%, 1 source treatment compared to the multiple-source treatments (100%, 6+ sources, 50%, 4+ sources, and 50%, 2 sources). The 100%, 1 source treatment was intermediate and not different ($P > 0.05$) from all other treatments except the 50%, 2 source treatment which had lower ($P \leq 0.05$) PWM. These results suggest that the single-source treatments, which had the lowest amount of mixing of piglets, generally had the highest pre-weaning mortality, regardless of whether they were cross-fostered. There were no differences ($P > 0.05$) between any treatments for the causes or timing of piglet PWM (Table 11.2).

Previous cross-fostering research has found variable effects for piglet pre-weaning performance. Some studies have found no effects on piglet performance to 21 d of age (Bishop, 2011; Heim et al., 2012). In contrast, the majority of other studies have found reduced pre-weaning performance for cross-fostered piglets (Horrell and Bennett, 1981; Stewart and Diekman, 1989; Giroux et al., 2000; Cecchinato et al., 2008; KilBride et al., 2014). Other studies have found positive effects of cross-fostering specifically for lower birth weight piglets (Marcatti, 1986; Neal and Irvin, 1991; Camargo et al., 2013). However, the cross-fostering protocols for these studies were often not defined, and those that were varied greatly. For example, the timing of cross-fostering varied markedly between studies. Giroux et al. (2000) cross-fostered piglets at 6 d of age and Horrell and Bennett (1981) cross-fostered piglets at 7 d of age, whereas Bishop (2011) and Heim et al. (2012) cross-fostered within 24 h of birth. The study of KilBride et al. (2014) was a survey of commercial farms, and showed considerable variation in the timing of cross-fostering; 31% of the farms used in the study cross-fostered within 24 h of birth, 52% within 71 h, and 17% cross-fostered after 72 h. Since the methodology used in these studies was highly variable, it is difficult to compare the results across studies. Without clear definition of cross-fostering protocols, it is unclear whether other factors such as piglet birth weight or litter size were confounded with treatments. However, in general, the majority of studies that cross-fostered within 24 h after birth (e.g., Bishop, 2011) found limited effects on piglet performance, whereas those that fostered later found negative effects (e.g., Horrell and Bennett, 1981).

The results of the current study were unexpected, generally showing reduced pre-weaning mortality for the multiple-source treatments over the single-source treatments, with no effects on weaning weight. Due to the lack of controlled research studies, there is no published information to use to validate or explain these results. Further research on the effect of the number of sources used to create cross-fostered litters is necessary to clearly establish the effects of cross-fostering piglets.

Tables

Table 11.1. Summary of sow characteristics by cross-fostering treatment.

Item.	Cross-fostering Treatment[1] 0% 1 source	100% 6+ sources	100% 1 source	50% 4+ sources	50% 2 sources	SEM	*P*-value
Total number of sows	25	25	25	21	26	-	-
Average sow parity[2]	4.4	4.8	4.4	4.5	4.6	0.48	0.90
Number of sows by parity[2]							
Parity 2 and 3	14	9	9	9	8	-	-
Parity 4 and 5	4	9	11	7	12	-	-
Parity 6+	7	7	5	5	6	-	-
Average sow body condition score[3]	3.68	3.62	3.70	3.60	3.94	0.112	0.19
Number of sows by body condition score[3]							
2.0 to 2.5	2	0	1	1	0	-	-
3.0 to 3.5	7	17	11	10	10	-	-
4.0 to 4.5	15	8	13	10	16	-	-
5	1	0	0	0	0	-	-
Average number of teats[4]							
Score 1	12.3	12.4	12.2	12.5	12.5	0.21	0.65
Score 2	1.9	2.2	2.2	2.0	2.2	0.20	0.22
Score 3	0.5[a]	0.3[ab]	0.2[ab]	0.1[b]	0.1[b]	0.10	0.04
Functional teats (Score 1+2)	14.2	14.6	14.4	14.5	14.6	0.17	0.13

[a,b]Means within a row with differing superscripts differ at $P \leq 0.05$.

[1]0%, 1 source = no cross-fostering, all piglets remaining with the sow of origin; 100%, 6+ sources = all piglets cross-fostered, from at least 6 other litters; 100%, 1 source = all piglets cross-fostered, from one other sow; 50%, 4+ sources = Half of the litter remaining with the sow of origin, half from at least 3 other litters; 50%, 2 sources = Half of the litter remaining with the sow of origin, half from one other litter.

[2]Parity = total number of litters including the one used in the study.

[3]On a scale of 1 extremely thin to 5 extremely fat.

[4]On a scale of 1 to 3: Score 1 = ideal, elongated and pointed with no visible defects; Score 2 = not ideal, teat end less elongated, but no visible defects; Score 3 = non-functional, teat severely damaged or visibly defective

Table 11.2. Least-squares means for the effects of cross-fostering treatment on piglet weight, average daily gain, pre-weaning mortality, and the causes and timing of mortality, as a percentage of total mortality within treatment.

Item.	Cross-fostering Treatment[1] 0% 1 source	100% 6+ sources	100% 1 source	50% 4+ sources	50% 2 sources	SEM	P-value
Number of piglets	350	350	350	294	364	-	-
Litter size							
After cross-fostering	14.0	14.0	14.0	14.0	14.0	-	-
At 7 d after birth	12.6[b]	13.4[a]	12.9[ab]	13.2[ab]	13.3[a]	0.17	0.004
At 14 d after birth	12.3	12.9	12.6	13.0	13.1	0.22	0.06
At weaning	12.1[b]	12.9[ab]	12.4[ab]	13.0[ab]	13.1[a]	0.23	0.01
Piglet weight, kg							
Birth	1.42	1.44	1.44	1.43	1.44	0.030	0.99
Weaning	5.98	5.78	5.9	5.91	5.82	0.155	0.89
Average daily gain, kg							
Weaned piglets	0.232	0.222	0.228	0.229	0.224	0.0074	0.89
All piglets[2]	0.205	0.207	0.208	0.216	0.212	0.0079	0.95
Pre-weaning mortality, %	13.4[a]	8.0[bc]	11.7[ab]	7.5[bc]	6.3[c]	-	0.01
Number of mortalities	47	28	41	22	23	-	-
Cause of mortality, % of total							
Crushed	57.4	46.4	53.7	45.5	56.5	-	0.88
Starvation	40.4	42.9	34.1	36.4	43.5	-	0.95
Other	2.1	10.7	12.2	18.2	0.0	-	0.40
Time of mortality, % of total							
Day 1 to 2	12.8	10.7	19.5	18.2	8.7	-	0.77
Day 1 to 7	83.0	64.3	78.0	77.3	91.3	-	0.29
Day 8 to weaning	17.0	35.7	22.0	22.7	8.7	-	0.29
Age of mortality, days[3]	6.3	7.2	6.6	6.7	5.5	-	0.85

[a,b,c]Means within a row with differing superscripts differ at $P \leq 0.05$.

[1]0%, 1 source = no cross-fostering, all piglets remaining with the sow of origin; 100%, 6+ sources = all piglets cross-fostered, from at least 6 other litters; 100%, 1 source = all piglets cross-fostered, from one other sow; 50%, 4+ sources = Half of the litter remaining with the sow of origin, half from at least 3 other litters; 50%, 2 sources = Half of the litter remaining with the sow of origin, half from one other litter.

[2]Transformed data using a square transformation to correct for normality and homogeneity of variance of the residuals.

[3]Transformed data using a square root transformation to correct for normality and homogeneity of variance of the residuals.

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